TEXT-BOOK OF GEOLOGY

BY

SIR ARCHIBALD GEIKIE, F.R.S.

PART ONE

NEW YORK
P. F. COLLIER & SON
MCMII
29

SCIENCE

SIR ARCHIBALD GEIKIE

SIR ARCHIBALD GEIKIE was born at Edinburgh on December 28, 1835. He is of French descent on the maternal side. He was educated at the High School and University of his native city, but has since been made a D.C.L. by Oxford, a D.Sc. by Cambridge and Dublin, and LL.D. by Edinburgh and St. Andrews. He entered the Geological Survey in 1855, and became successively Director of the Geological Survey of Scotland, Murchison Professor of Geology and Mineralogy in Edinburgh University, Director of the Museum of Practical Geology in Jermyn Street, London, Foreign Secretary of the Royal Society, President of the Geological Society and President of the British Association. He is a Correspondent of the Institute of France, of the Lincei, Rome, of the Academies of Berlin, Vienna, Belgium, Stockholm, Turin, Munich, Christiania, Göttingen, and so forth. He has been the recipient of innumerable medals. Among his numerous publications we have selected for reproduction the "Text-Book of Geology," which has been translated into almost every European language.

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PREFACE TO THE THIRD EDITION

The present edition of this Text-book has been entirely revised, and in some portions recast or rewritten, so as to bring it abreast of the continuous advance of Geological Science. The additions made to the text, which extend to every branch of the subject, increase the volumes by about 270 pages. Care has been taken to preserve a characteristic feature of former editions by inserting references to the more important memoirs and papers, where the student will find fuller information than can be given in a Text-book.

While the book was passing through the press I received from my friend Professor Zirkel the first volume of the new edition of his great text-book of Petrography, but too late to avail myself of its assistance. I can only now recommend it as an indispensable part of the outfit of every serious student of the petrographical section of Geology.

In the revision of the stratigraphical portion of this work I have been assisted with suggestions and information by my colleagues, Mr. Topley, Mr. H. B. Woodward, Mr. E. T. Newton, and Mr. C. Reid, to whom my best thanks are due.

Museum, Jermyn Street,
1st August 1893.

FROM THE PREFACE TO THE FIRST EDITION

THE method of treatment adopted in this Text-book is one which, while conducting the class of Geology in the University of Edinburgh, I have found to afford the student a good grasp of the general principles of the science, and at the same time a familiarity with and interest in details of which he is enabled to see the bearing in the general system of knowledge. A portion of the volume appeared in the autumn of 1879 as the article "Geology" in the *Encyclopædia Britannica*. My leisure since that date has been chiefly devoted to expanding those sections of the treatise which could not be adequately developed in the pages of a general work of reference.

While the book will not, I hope, repel the general reader who cares to know somewhat in detail the facts and principles of one of the most fascinating branches of natural history, it is intended primarily for students, and is therefore adapted specially for their use. The digest given of each subject will be found to be accompanied by references to memoirs where a fuller statement may be sought. It has long been a charge against the geologists of Great Britain that, like their countrymen in general, they are apt to be somewhat insular in their conceptions, even in regard to their own branch of science. Of course, specialists who have devoted themselves to the investigation of certain geological formations or of a certain group of fossil animals, have made themselves familiar with what has been written upon their subject in other countries. But I am afraid there is still not a little truth in the charge, that the general body of geologists here is but vaguely acquainted with geological types and illustrations other than such as have been drawn from the area of the British Isles. More particularly is the accusation true in regard to American geology. Comparatively few of us have any adequate conception of the simplicity and grandeur of the examples by which the principles of the science have been enforced on the other side of the Atlantic.

Fully sensible of this natural tendency, I have tried to keep it in constant view as a danger to be avoided as far as the conditions of my task would allow. In a text-book designed for use in Britain, the illustrations must obviously be in the first place British. A truth can be enforced much more vividly by an example culled from familiar ground than by one taken from a distance. But I have striven to widen the vision of the student by indicating to him that while the general principles of the science remain uniform, they receive sometimes a clearer, sometimes a somewhat different, light from the rocks of other countries than our own. If from these references he is induced to turn to the labors of our fellow workers on the Continent, and to share my respect and admiration for them, a large part of my design will have been accomplished. If, further, he is led to study with interest the work of our brethren across the Atlantic, and to join in my hearty regard for it and for them, another important section of my task will have been fulfilled. And if in perusing these pages he should find in them any stimulus to explore nature for himself, to wander with the enthusiasm of a true geologist over the length and breadth of his own country, and, where opportunity offers, to extend his experience and widen his sympathies by exploring the rocks of other lands, the remaining and chief part of my aim would be attained.

The illustrations of Fossils in Book VI. have been chiefly drawn by Mr. George Sharman; a few by Mr. B. N. Peach, and one or two by Dr. R. H. Traquair, F.R.S., to all of whom my best thanks are due. The publishers having become possessed of the wood-blocks of Sir Henry de la Beche's "Geological Observer," I gladly made use of them as far as they could be employed in Books III. and IV. Sir Henry's sketches were always both clear and artistic, and I hope that students will not be sorry to see some of them revived. They are indicated by the letter (*B*). The engravings of the microscopic structure of rocks are from my own drawings, and I have also availed myself of materials from my sketch-books. The frontispiece is a reduction of a drawing by Mr. W. H. Holmes, whose pictures of the scenery in the Far West of the United States are by far the most remarkable examples yet attained of the union of artistic effectiveness with almost diagrammatic geological distinctness and accuracy. Captain Dutton, of the Geological Survey of the United States, furnished me with this drawing, and also requested Mr. Holmes to make for me the cañon-sections given in Book VII. To both of these kind friends I desire to acknowledge my indebtedness.

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TEXT-BOOK OF GEOLOGY

INTRODUCTION

GEOLOGY is the science which investigates the history of the Earth. Its object is to trace the progress of our planet from the earliest beginnings of its separate existence, through its various stages of growth, down to the present condition of things. It unravels the complicated processes, involving vast geographical revolutions, by which each continent and country has been built up, tracing out the origin of their materials and the manner in which their existing outlines have been determined. It likewise follows into detail the varied sculpture of mountain and valley, crag and ravine.

Nor does this science confine itself merely to changes in the inorganic world. Geology shows that the present races of plants and animals are the descendants of other and very different races that once peopled the earth. It teaches that there has been a progress of the inhabitants, as well as one of the globe on which they have dwelt; that each successive period in the earth's history, since the introduction of living things, has been marked by characteristic types of the animal and vegetable kingdoms; and that, how imperfectly soever they may have been preserved or may be deciphered, materials exist for a history of life upon the planet. The geographical distribution of existing faunas and floras is often made clear and intelligible by geological evidence; and in a similar way, light is thrown upon some of the remoter phases in the history of man himself.

A subject so comprehensive as this must require a wide and varied basis of evidence. One of the characteristics of geology is to gather evidence from sources which, at first sight, seem far removed from its scope, and to seek aid from almost every other leading branch of science. Thus, in dealing with the earliest conditions of the planet, the geologist must fully avail himself of the labors of the astronomer. Whatever is ascertainable by telescope, spectroscope, or chemical analysis, regarding the constitution of other heavenly bodies, has a geological bearing. The experiments of the physicist, undertaken to determine conditions of matter and of energy, may sometimes be taken as the starting-point of geological investigation. The work of the chemical laboratory forms the foundation of a vast and increasing mass of geological inquiry. To the botanist, the zoologist, even to the unscientific, if observant, traveller by land or sea, the geologist turns for information and assistance.

But while thus culling freely from the dominions of other sciences, geology claims, as its peculiar territory, the rocky framework of the globe. In the materials composing that framework, their composition and arrangement, the processes of their formation, the changes which they have individually undergone, and the grand terrestrial revolutions to which they bear witness, lie the main data of geological history. It is the task of the geologist to group these elements in such a way that they may be made to yield up their evidence as to the march of events in the evolution of the planet. He finds that they have in large measure arranged themselves in chronological sequence—the oldest lying at the bottom and the newest at the top. Relics of an ancient sea-floor are overlain with traces of a vanished land-surface; these are in turn covered by the deposits of a former lake, above which once more appear proofs of the return of the sea. Among these rocky records, too, lie the lavas and ashes of long-extinct volcanoes. The ripple left upon a sandy beach, the cracks formed by the sun's heat upon the muddy bottom of a dried-up pool, the very imprint of the drops of a passing rain-shower, have all been accurately preserved, and often bear witness to geographical conditions widely different from those that exist where such markings are now found.

But it is mainly by the remains of plants and animals imbedded in the rocks that the geologist is guided in unravelling the chronological succession of geological changes. He has found that a certain order of appearance characterizes these organic remains; that each successive group of rocks is marked by its own special types of life; that these types can be recognized, and the rocks in which they occur can be correlated, even in distant countries, where no other means of comparison are available. At one moment, he has to deal with the bones of some large mammal scattered through a deposit of superficial gravel, at another time, with the minute foraminifers and ostracods of an upraised sea-bottom. Corals and crinoids, crowded and crushed into a massive limestone on the spot where they lived and died, ferns and terrestrial plants matted together into a bed of coal where they originally grew, the scattered shells of a submarine sand-bank, the snails and lizards that left their mouldering remains within a hollow tree, the insects that have been imprisoned within the exuding resin of old forests, the footprints of birds and quadrupeds, or the trails of worms left upon former shores—these, and innumerable other pieces of evidence, enable the geologist to realize in some measure what the vegetable and animal life of successive periods has been, and what geographical changes the site of every land has undergone.

It is evident that to deal successfully with these varied materials, a considerable acquaintance with different branches of science is desirable. The fuller and more accurate the knowledge which the geologist has of kindred branches of inquiry, the more interesting and fruitful will be his own researches. From its very nature, geology demands on the part of its votaries wide sympathy with investigation in almost every branch of natural science. Especially necessary is a tolerably large acquaintance with the processes now at work in changing the surface of the earth, and of at least those forms of plant and animal life whose remains are apt to be preserved in geological deposits, or which, in their structure and habitat, enable us to realize what their forerunners were.

It has often been insisted upon that the Present is the key to the Past; and in a wide sense this assertion is eminently true. Only in proportion as we understand the present, where everything is open on all sides to the fullest investigation, can we expect to decipher the past, where so much is obscure, imperfectly preserved, or not preserved at all. A study of the existing economy of nature ought evidently to be the foundation of the geologist's training.

While, however, the present condition of things is thus employed, we must obviously be on our guard against the danger of unconsciously assuming that the phase of nature's operations which we now witness has been the same in all past time; that geological changes have taken place, in former ages, in the manner and on the scale which we behold to-day, and that at the present time all the great geological processes, which have produced changes in past eras of the earth's history, are still existent and active. Of course, we may assume this uniformity of action, and use the assumption as a working hypothesis. But it ought not to be allowed a firmer footing, nor on any account be suffered to blind us to the obvious truth that the few centuries, wherein man has been observing nature, form much too brief an interval by which to measure the intensity of geological action in all past time. For aught we can tell, the present is an era of quietude and slow change, compared with some of the eras that have preceded it. Nor can we be sure that when we have explored every geological process now in progress, we have exhausted all the causes of change which, even in comparatively recent times, have been at work.

In dealing with the Geological Record, as the accessible solid part of the globe is called, we cannot too vividly realize that, at the best, it forms but an imperfect chronicle. Geological history cannot be compiled from a full and continuous series of documents. Owing to the very nature of its origin, the record is necessarily from the first fragmentary, and it has been further mutilated and obscured by the revolutions of successive ages. Even where the chronicle of events is continuous, it is of very unequal value in different places. In one case, for example, it may present us with an unbroken succession of deposits, many thousands of feet in thickness, from which, however, only a few meagre facts as to geological history can be gleaned. In another instance, it brings before us, within the compass of a few yards, the evidence of a most varied and complicated series of changes in physical geography, as well as an abundant and interesting suite of organic remains. These and other characteristics of the geological record will become more apparent and intelligible to the student as he proceeds in the study of the science.

In the present volumes the subject will be distributed under the following leading divisions:

1. *The Cosmical Aspects of Geology.*—It is desirable to realize some of the more important relations of the earth to the other members of the solar system, of which it forms a part, seeing that geological phenomena are largely the result of these relations. The form and motions of the planet may be briefly touched upon, and attention should be directed to the way in which these planetary movements influence geological change. The light cast upon the early history of the earth by researches into the composition of the sun and stars deserves notice here.

2. *Geognosy—An Inquiry into the Materials of the Earth's Substance.*—This division describes the constituent parts of the earth, its envelopes of air and water, its solid crust, and the probable condition of its interior. Especially, it directs attention to the more important minerals of the crust, and the chief rocks of which that crust is built up. In this way, it lays a foundation of knowledge regarding the nature of the materials constituting the mass of the globe, whence we may next proceed to investigate the processes by which these materials are produced and altered.

3. *Dynamical Geology* embraces an investigation of the operations which lead to the formation, alteration, and disturbance of rocks, and calls in the aid of physical and

chemical experiment in elucidation of these operations. It considers the nature and operation of the processes that have determined the distribution of sea and land, and have molded the forms of the terrestrial ridges and depressions. It further investigates the geological changes which are in progress over the surface of the land and floor of the sea, whether these are due to subterranean disturbance, or to the effect of operations above ground. Such an inquiry necessitates a careful study of the existing economy of nature, and forms a fitting introduction to the investigation of the geological changes of former periods. This and the previous section, including most of what is embraced under Physical Geography and Petrogeny or Geogeny, will here be discussed more in detail than is usual in geological treatises.

4. *Geotectonic, or Structural Geology—the Architecture of the Earth.*—This section of the investigation, applying the results arrived at in the previous division, discusses the actual arrangement of the various materials composing the crust of the earth. It proves that some have been formed in beds or strata, whether by the deposit of sediment on the floor of the sea, or by the slow aggregation of organic forms, that others have been poured out from subterranean sources in sheets of molten rock, or in showers of loose dust, which have been built up into mountains and plateaus. It further shows that rocks originally laid down in almost horizontal beds have subsequently been crumpled, contorted, dislocated, invaded by igneous masses from below, and rendered sometimes crystalline. It teaches, too, that wherever exposed above sea-level, they have been incessantly worn down, and have often been depressed, so that older lie buried beneath later accumulations.

5. ***Palæontological** Geology.*—This branch of the subject deals with the organic forms which are found preserved in the rocks of the crust of the earth. It includes such questions as the manner in which the remains of plants and animals are entombed in sedimentary accumulations, the relations between extinct and living types, the laws which appear to have governed the distribution of life in time and in space, the nature and use of the evidence from organic remains regarding former conditions of physical geography, and the relative importance of different genera of animals and plants in geological inquiry.

6. *Stratigraphical Geology.*—This section might be called Geological History, or Historical Geology. It works out the chronological succession of the great formations of the earth's crust, and endeavors to trace the sequence of events of which they contain the record. More particularly, it determines the order of succession of the various plants and animals which in past time have peopled the earth, and thus, by ascertaining what has been the grand march of life upon the planet, seeks to unravel the story of the earth as made known by the rocks of the crust. Further, by comparing the sequence of rocks in one country with that of those in another, it furnishes materials for enabling us to picture the successive stages in the geographical evolution of the various portions of the earth's surface.

7. *Physiographical Geology*, starting from the basis of fact laid down by stratigraphical geology regarding former geographical changes, embraces an inquiry into the history of the present features of the earth's surface—continental ridges and ocean basins, plains, valleys, and mountains. It investigates the structure of mountains and valleys, compares the mountains of different countries, and ascertains

the relative geological dates of their upheaval. It explains the causes on which local differences of scenery depend, and shows under what very different circumstances, and at what widely separated intervals, the varied contours, even of a single country, have been produced.

BOOK I

COSMICAL ASPECTS OF GEOLOGY

BEFORE geology had attained to the position of an inductive science, it was customary to begin all investigations into the history of the earth by propounding or adopting some more or less fanciful hypothesis, in explanation of the origin of our planet or of the universe. Such preliminary notions were looked upon as essential to a right understanding of the manner in which the materials of the globe had been put together. To the illustrious James Hutton (1785) geologists are indebted, if not for originating, at least for strenuously upholding the doctrine that it is no part of the province of geology to discuss the origin of things. He taught them that in the materials from which geological evidence is to be compiled there can be found "no traces of a beginning, no prospect of an end." In England, mainly to the influence of the school which he founded, and to the subsequent rise of the Geological Society (1807), which resolved to collect facts instead of fighting over hypotheses, is due the disappearance of the crude and unscientific cosmologies of previous centuries.

But there can now be little doubt that in the reaction against the visionary and often grotesque speculations of earlier writers, geologists were carried too far in an opposite direction. In allowing themselves to believe that geology had nothing to do with questions of cosmogony, they gradually grew up in the conviction that such questions could never be other than mere speculation, interesting or amusing as a theme for the employment of the fancy, but hardly coming within the domain of sober and inductive science. Nor would they soon have been awakened out of this belief by anything in their own science. It is still true that in the data with which they are accustomed to deal, as comprising the sum of geological evidence, there can be found no trace of a beginning, though there is ample proof of constant, upward progression from some invisible starting-point. The oldest rocks which have been discovered on any part of the globe have possibly been derived from other rocks older than themselves. Geology by itself has not yet revealed, and is little likely ever to reveal, a portion of the first solid crust of our globe. If, then, geological history is to be compiled from direct evidence furnished by the rocks of the earth, it cannot begin at the beginning of things, but must be content to date its first chapter from the earliest period of which any record has been preserved among the rocks.

Nevertheless, though, in its usual restricted sense, geology has been, and must ever be, unable to reveal the earliest history of our planet, it no longer ignores, as mere speculation, what is attempted in this subject by its sister sciences. Astronomy, physics and chemistry have in late years all contributed to cast much light on the earliest stages of the earth's existence, previous to the beginning of what is commonly regarded as geological history. Whatever extends our knowledge of the former conditions of our globe may be legitimately claimed as part of the domain of geological inquiry. If Geology, therefore, is to continue worthy of its name as the science of the earth, it must take cognizance of these recent contributions from other sciences. It can no longer be content to begin its annals with the records of the oldest rocks, but must endeavor to grope its way through the ages which preceded the formation of any rocks. Thanks to the results achieved with the telescope, the spectroscope, and the chemical laboratory, the story of these earliest ages of our earth is every year becoming more definite and intelligible.

I. Relations of the Earth in the Solar System

As a prelude to the study of the structure and history of the earth, some of the general relations of our planet to the solar system may here be noticed. The investigations of recent years, showing the community of substance between the different members of that system, have revived and have given a new form and meaning to the well-known nebular hypothesis of Kant, Laplace and W. Herschel, which sketched the progress of the system from the state of an original nebula to its existing condition of a central incandescent sun with surrounding cool planetary bodies. According to this hypothesis, the nebula, originally diffused at least as far as the furthest member of the system, began to condense toward the centre, and in so doing threw off or left behind successive rings. These, on disruption and further condensation, assumed the form of planets, sometimes with a further formation of rings, which in the case of Saturn remain, though in other planets they have broken up and united into satellites.

Accepting this view, we should expect the matter composing the various members of the solar system to be everywhere nearly the same. The fact of condensation round centres, however, indicates probable differences of density throughout the nebula. That the materials composing the nebula may have arranged themselves according to their respective densities, the lightest occupying the exterior, and the heaviest the interior of the mass, is suggested by a comparison of the densities of the various planets. These densities are usually estimated as in the following table, that of the earth being taken as the unit:

Density of the	Sun	0·25
"	Mercury	1·12
"	Venus	1·03
"	Earth	1·00
"	Mars	0·70
"	Jupiter	0·24
"	Saturn	0·13
"	Uranus	0·17
"	Neptune	0·16

It is to be observed, however, that "the densities here given are mean densities, assuming that the *apparent* size of the planet or sun is the *true* size, *i.e.* making no allowance for thousands of miles deep of cloudy atmosphere. Hence the numbers for Jupiter, Saturn and Uranus are certainly too small, that for the sun much too small."[1] Taking the figures as they stand, while they do not indicate a strict progression in the diminution of density, they state that the planets near the sun possess a density about twice as great as that of granite, but that those lying toward the outer limits of the system are composed of matter as light as cork. Again, in some cases, a similar relation has been observed between the densities of the satellites and

[1] Prof. Tait, MS. note.

their primaries. The moon, for example, has a density little more than half that of the earth. The first satellite of Jupiter is less dense, though the other three are said to be more dense than the planet. Further, in the condition of the earth itself, a very light gaseous atmosphere forms the outer portion, beneath which lies a heavier layer of water, while within these two envelopes the materials forming the solid substance of the planet are so arranged that the outer layer or crust has only about half the density of the whole globe.

According to the hypothesis now under consideration it is conceived that, in the gradual condensation of the original nebula, each successive mass left behind represented the density of its parent shell, and consisted of progressively heavier matter.[2] The remoter planets, with their low densities and vast absorbing atmospheres, may be supposed to consist of metalloids, like the outer parts of the sun's atmosphere, while the interior planets are no doubt mainly metallic. The rupture of each planetary ring would, it is thought, raise the temperature of the resultant nebulous planet to such a height as to allow the vapors to rearrange themselves by degrees in successive layers, or rather shells, according to densities. And when the planet gave off a satellite, that body might be expected to possess the composition and density of the outer layers of its primary.[3]

For many years, the only evidence available as to the

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[2] On the origin of Satellites, see the researches of Prof. G. H. Darwin, Phil. Trans. (1879) clxx. p. 535. Proc. Roy. Soc. xxx. p. 1.

[3] Lockyer in Prestwich's Inaugural Lecture, Oxford, 1875, and in Manchester Lectures, Why the Earth's Chemistry is as it is. Readers interested in the historical development of geological opinion will find much suggestive matter bearing on the questions discussed above, in De la Beche's "Researches in Theoretical Geology," 1834—a work notably in advance of its time.

actual composition of other heavenly bodies than our own earth was furnished by the *meteorites*, or fallen stars, which from time to time have entered our atmosphere from planetary space, and have descended upon the surface of the globe.[4] Subjected to chemical analysis, these foreign bodies show considerable diversities of composition; but in no case have they yet revealed the existence of any element not already recognized among terrestrial materials. They have been classified in three groups: *Siderites*, composed chiefly of iron; *Siderolites*, consisting partly of iron and partly of various stony materials; and *Aerolites*, formed almost entirely of such stony minerals. Twenty-four of our elements have been detected in meteorites. Those most commonly found are iron, nickel, phosphorus, sulphur, carbon, oxygen, silicon, magnesium, calcium and aluminium. Less frequent or occurring in smaller quantities are hydrogen, nitrogen, chlorine, lithium, sodium, potassium, titanium, chromium, manganese, cobalt, arsenic, antimony, tin and copper. These various elements occur for the most part in a state of combination. The iron exists as an alloy with nickel, the phosphorus is combined with nickel and iron, the silicon is combined with oxygen and various bases. A few of the elements occur in a free state. Thus hydrogen and nitrogen are found as occluded gases and carbon as

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[4] On meteorites consult Partsch, "Die Meteoriten," Vienna, 1843. Rose, Abhand. königl. Akad. Berlin, 1863. Rammelsberg, "Die Chemische Natur der Meteoriten," 1870–9. Tschermak, Sitzb. Akad. Wissen. Vienna (1875), lxxi.; "Die Mikroskopische Beschaffenheit der Meteoriten," Stuttgart, 1885. Daubrée, "Etudes Synthétiques de Géologie Expérimentale," 1879; Compt. rend. cvi. (1888), 1671–1682 (compare Amer. Journ. Sci. xlii. [1891], p. 413). S. Meunier, "Le Ciel Géologique," 1871; "Météorites," 1884. Brezina und Cohen, "Die Structur und Zusammensetzung der Meteoreisen," Stuttgart, 1886. W. Flight, Geol. Mag. 1875, Pop. Sci. Rev. new ser. i. p. 390. Proc. Roy. Soc. xxxiii. p. 343. A. W. Wright, Amer. Journ. ser. 3, xi. p. 253; xii. p. 165. L. Fletcher, "An Introduction to the Study of Meteorites," British Museum Catalogue, 1886.

graphite, rarely as diamond. Of combinations of elements in meteorites some, not yet recognized among terrestrial minerals, comprise alloys of iron and nickel and various sulphides and silicates. But others have been identified with well-known minerals of the earth's crust, including olivine, enstatite and bronzite, diopside and augite, hornblende, anorthite and labradorite, magnetite and chromite, etc. There is likewise a carbonaceous group of meteorites containing carbon, both amorphous and as black diamond, also combined with hydrogen and oxygen, and in some cases combustible, with a bituminous smell. Some iron meteorites contain a large proportion of occluded hydrogen, nitrogen, or carbonic oxide, occasionally as much as six times the volume of the meteorite itself.

Various theories have been propounded as to the origin or source of those bodies which come to our planet from space. But at present we possess no satisfactory basis of fact on which to speculate. Whether these stones belong to the solar system, or, as seems more probable, reach us from remoter space, they prove that some at least of the elements and minerals with which we are familiar extend beyond our planet.

But, in recent years, a far more precise and generally available method of research into the composition of the heavenly bodies has been found in the application of the spectroscope. By means of this instrument, the light emitted from self-luminous bodies can be analyzed in such a way as to show what elements are present in their intensely hot luminous vapor. When the light of the incandescent vapor of a metal is allowed to pass through a properly arranged prism, it is seen to give a spectrum consisting of transverse bright lines only. This is termed a *radiation-spectrum.* Each element appears to have its own characteristic arrangement of lines, which in general retain the same relative position, intensity and colors. Moreover, gases and the vapors of solid bodies are found to intercept those rays of light which they themselves emit. The spectrum of sodium-vapor, for example, shows among others two bright orange lines. If therefore white light, from some hotter light-source, passes through the vapor of sodium, these two bright lines become dark lines, the light being exactly cut off which would have been given out by the sodium itself. This is called an *absorption-spectrum.*

From this method of examination, it has been inferred that many of the elements of which our earth is composed must exist in the state of incandescent vapor in the atmosphere of the sun. Thirty-two metals have been thus identified, including aluminium, barium, manganese, lead, calcium, cobalt, potassium, iron, zinc, copper, nickel, sodium and magnesium. These elements, or at least substances which give the same groups of lines as the terrestrial elements with which they have been identified, do not occur promiscuously diffused throughout the outer mass of the sun. According to Mr. Lockyer's first observations, they appear to succeed each other in relation to their respective densities. Thus the coronal atmosphere which, as seen in total eclipses, extends to so prodigious a distance beyond the disk of the sun, consists mainly of subincandescent hydrogen and another element which may be new. Beneath this external vaporous envelope lies the chromosphere, where the vapors of incandescent hydrogen, calcium and magnesium can be detected. Further inward the spot-zone shows the presence of sodium, titanium, etc.; while still lower, a layer (the *reversing* layer) of intensely hot vapors, lying probably next to the inner brilliant photosphere, gives spectroscopic evidence of the existence of incandescent iron, manganese, cobalt, nickel, copper, and other well-known terrestrial metals.[5]

It is to be observed, however, that in these spectroscopic researches the decomposition of the elements by electrical action was not considered. The conclusions embodied in the foregoing paragraph have been founded on the idea that the lines seen in the spectrum of any element are all due to the vibrations of the molecules of that element. But Mr. Lockyer has suggested that this view may after all be but a rough approximation to the truth; that it may be more accurate to say, as a result of the facts already acquired, that there exist basic elements common to calcium, iron, etc., and to the solar atmosphere, and that the spectrum of each body is a summation of the spectra of various molecular complexities which can exist at different temperatures, the simplest only being found in the hottest part of the sun.[6]

The spectroscope has likewise been successfully applied by Mr. Huggins and others to the observation of the fixed stars and nebulæ, with the result of establishing a similarity of elements between our own system and other bodies in

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[5] On spectroscopic research as applied to the sun, see Kirchhoff and Bunsen, "Researches on Solar Spectrum," etc., 1863; Angström, "Recherches sur le Spectre normal du Soleil"; Lockyer, "Solar Physics," 1873, and "Studies in Spectrum Analysis" (International Series), 1878; Huggins and Miller, Proc. Roy. Soc. xii., Phil. Trans. 1864; Roscoe's "Spectrum Analysis," with authorities there cited. An ingenious theory to account for the conservation of solar energy was suggested by the late Sir C. W. Siemens (Proc. Roy. Soc. xxxiii. (1881) p. 389). It requires the presence of aqueous vapor and carbon compounds in stellar space, which are dissociated and drawn into the solar photosphere, where they burst into flame with a large development of heat, and then passing into aqueous vapor and carbonic anhydride or oxide, flow to the solar equator whence they are projected into space.

[6] See also the opposite views of Dewar and Liveing, Proc. Roy. Soc. xxx. p. 93, and H. W. Vogel, Nature, xxvii. p. 233.

sidereal space. In the radiation-spectra of nebulæ, Mr. Huggins finds the hydrogen lines very prominent; and he conceives that they may be glowing masses of that element. Prof. Tait has suggested, on the other hand, that they are more probably clouds of stones frequently colliding and thus giving off incandescent gases. Sir William Thomson (now Lord Kelvin) favors this view, which is further amply supported by spectroscopic observations. Among the fixed stars, absorption-spectra have been recognized, pointing to a structure resembling that of our sun, viz. an incandescent nucleus which may be solid or liquid or of very highly compressed gas, but which gives a continuous spectrum and which is surrounded with an atmosphere of glowing vapor.[7] Those stars which show the simplest spectra are believed to have the highest temperature, and in proportion as they cool their materials will become more and more differentiated into what we call elements. The most brilliant or hottest stars show in their spectra only the lines of gases, as hydrogen. Cooler stars, like our sun, give indications of the presence, in addition, of the metals—magnesium, sodium, calcium, iron. A still lower temperature is marked by the appearance of the other metals, metalloids, and compounds.[8] The sun would thus be a star considerably advanced in the process of differentiation or association of its atoms. It contains, so far as we know, no metalloid except carbon, and possibly oxygen, nor any compound, while stars like Sirius show the presence only of hydrogen, with but a feeble proportion of metallic vapors; and, on the other hand, the red stars indicate by their spectra that their metallic vapors have

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[7] Huggins, Proc. Roy. Soc. 1863–66, and Brit. Assoc. Lecture (Nottingham, 1866); Huggins and Miller, Phil. Trans. 1864.

[8] Lockyer, Comptes rendus, Dec. 1873.

entered into combination, whence it is inferred that their temperature is lower than that of our sun.

More recently, however, another view of the evolution of stars has been propounded by Mr. Lockyer. He conceives that all self-luminous cosmical bodies are composed either of swarms of meteorites, or of masses of vapor produced by collisions of meteorites: that stars, comets and nebulæ are only different phases of the same series of changes; that where the temperature of a star is increasing the star consists of a meteor-swarm, which by constant collision of its individual meteorites is gradually being vaporized by heat; and that after volatilization cooling sets in and the vapor finally condenses into a globe.[9]

II. Form and Size of the Earth

Further confirmation of some of the foregoing views as to the order of planetary evolution is furnished by the form of the earth and the arrangement of its component materials.

That the earth is an oblate spheroid, and not a perfectly spherical globe, was discovered and demonstrated by Newton. He even calculated the amount of ellipticity long before any measurement had confirmed such a conclusion. During the present century numerous arcs of the meridian have been measured, chiefly in the northern hemisphere. From a series made by different observers between the latitudes of Sweden and the Cape of Good Hope, Bessel obtained the following data for the dimensions of the earth:

Equatorial diameter . . .	41,847,192	feet, or	7925·604	miles
Polar diameter	41,707,314	"	7899·114	"
Amount of polar flattening .	139,768	"	26·471	"

[9] "The Meteoritic Hypothesis," 1890.

The equatorial circumference is thus a little less than 25,000 miles, and the difference between the polar and equatorial diameters (nearly 26½ miles) amounts to about $\frac{1}{300}$th of the equatorial diameter.[10] More recently, however, it has been shown that the oblate spheroid indicated by these measurements is not a symmetrical body, the equatorial circumference being an ellipse instead of a circle. The greater axis of the equator lies in long. 8° 15′ W.—a meridian passing through Ireland, Portugal, and the northwest corner of Africa, and cutting off the northeast corner of Asia in the opposite hemisphere.[11]

The polar flattening, established by measurement and calculation as that which would necessarily have been assumed by an originally plastic globe in obedience to the movement of rotation, has been cited as evidence that the earth was once in a plastic condition. Taken in connection with the analogies supplied by the sun and other heavenly bodies, this inference appeared to be well grounded.[12] More recently, however, it has been contended that even in a truly solid body a polar flattening might be developed under the influence of rotation.[13]

Though the general spheroidal form of our planet, and

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[10] Herschel, "Astronomy," p. 185.

[11] A. R. Clarke, Phil. Mag. August, 1878; Encyclopædia Britannica, 9th edit. x. 172.

[12] It was opposed by Mohr ("Geschichte der Erde," p. 472), who, adopting a suggestion long ago made by Playfair, endeavored to show that the polar flattening can be accounted for by greater denudation of the polar tracts, exposed as these have been by the heaping up of the oceanic waters toward the equator in consequence of rotation. He dwelt chiefly on the effects of glaciers in lowering the land, but as Pfaff has pointed out, the work of erosion is chiefly performed by other atmospheric forces that operate rather toward the equator than the poles ("Allgemeine Geologie als exacte Wissenschaft," p. 6). Compare Naumann, Neues Jahrb. 1871, p. 250. Nevertheless, Mohr undoubtedly recalled attention to a conceivable cause by which, in spite of polar elevation or equatorial subsidence, the external form of the planet might be preserved.

[13] See in particular the papers by Mr. C. Chree. Phil. Mag. 1891, pp. 233 and 342.

probably the general distribution of sea and land, are referable to the early effects of rotation on a fluid or viscous mass, it is certain that the present details of its surface-contours are of comparatively recent date. Speculations have been made as to what may have been the earliest character of the solid surface, whether it was smooth or rough, and particularly whether it was marked by any indication of the existing continental elevations and oceanic depressions. So far as we can reason from geological evidence, there is no proof of any uniform superficies having ever existed. Most probably the first formed crust broke up irregularly, and not until after many successive corrugations did the surface acquire stability. Some writers have imagined that at first the ocean spread over the whole surface of the planet. But of this there is not only no evidence, but good reason for believing that it never could have taken place. As will be alluded to in a later page, the preponderance of water in the southern hemisphere seems to indicate some excess of density in that hemisphere. This excess can hardly have been produced by any change since the materials of the interior ceased to be mobile; it must therefore be at least as ancient as the condensation of water on the earth's surface. Hence there was probably from the beginning a tendency in the ocean to accumulate in the southern rather than in the northern hemisphere.

That land existed from the earliest ages of which we have any record in rock-formations, is evident from the obvious fact that these formations themselves consist in great measure of materials derived from the waste of land. When the student, in a later part of these volumes, is presented with the proofs of the existence of enormous masses of sedimentary deposits, even among some of the oldest geological systems, he will perceive how important must have been the tracts of land that could furnish such piles of detritus.

The tendency of modern research is to give probability to the conception, first outlined by Kant, that not only in our own solar system, but throughout the regions of space, there has been a common plan of evolution, and that the matter diffused through space in nebulæ, stars and planets is substantially the same as that with which we are familiar. Hence the study of the structure and probable history of the sun and the other heavenly bodies comes to possess an evident geological interest, seeing that it may yet enable us to carry back the story of our planet far beyond the domain of ordinary geological evidence, and upon data not less trustworthy than those furnished by the rocks of the earth's crust.

III. Movements of the Earth in their Geological Relations

We are here concerned with the earth's motions in so far only as they materially influence the progress of geological phenomena.

§ 1. **Rotation.**—In consequence of its angular momentum at its original separation, the earth rotates on its axis. The rate of rotation has once been much more rapid than it now is (p. 46). At present a complete rotation is performed in about twenty-four hours, and to it is due the succession of day and night. So far as observation has yet gone, this movement is uniform, though recent calculations of the influence of the tides in retarding rotation tend to show that a very slow diminution of the angular velocity is in progress. If this be so, the length of the day and night will slowly increase until finally the duration of the day and that of the year will be equal. The earth will then have reached the condition into which the moon has passed relatively to the earth, one-half being in continual day, the other in perpetual night.

The linear velocity due to rotation varies in different places, according to their position on the surface of the planet. At each pole there can be no velocity, but from these two points toward the equator there is a continually increasing rapidity of motion, till at the equator it is equal to a rate of 507 yards in a second.

To the rotation of the earth are due certain remarkable influences upon currents of air circulating either toward the equator or toward the poles. Currents which move from polar latitudes travel from parts of the earth's surface where the velocity due to rotation is small, to others where it is great. Hence they lag behind, and their course is bent more and more westward. An air current, quitting the north polar or north temperate regions as a north wind, is deflected out of its course, and becomes a northeast wind. On the opposite side of the equator, a similar current setting out straight for the equator, is changed into a southeast wind. Hence, as is well known, the Trade-winds have their characteristic westward deflection. On the other hand, a current setting out northward or southward from the equator, passes into regions having a less velocity due to rotation than it possesses itself, and hence it travels on in advance and appears to be gradually deflected eastward. The aërial currents, blowing steadily across the surface of the ocean toward the equator, produce oceanic currents which unite to form the westward flowing Equatorial current.

It has been maintained by Von Baer,[14] that a certain deflection is experienced by rivers that flow in a meridional direction, like the Volga and Irtisch. Those travelling poleward are asserted to press upon their eastern rather than their western banks, while those which run in the opposite direction are stated to be thrown more against the western than the eastern. When, however, we consider the comparatively small volume, slow motion, and continually meandering course of rivers, it may reasonably be doubted whether this *vera causa* can have had much effect generally in modifying the form of river channels.

§ 2. **Revolution.**—Besides turning on its axis, the globe performs a movement round the sun, termed revolution. This movement, accomplished in rather more than 365 days, determines for us the length of our year, which is, in fact, merely the time required for one complete revolution. The path or orbit followed by the earth round the sun is not a perfect circle but an ellipse, with the sun in one of the foci, the mean distance of the earth from the sun being 92,800,000, the present aphelion distance 94,500,000, and the perihelion distance 91,250,000 miles. By slow secular variations, the form of the orbit alternately approaches to and recedes from that of a circle. At the nearest possible approach between the two bodies,

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[14] "Ueber ein allgemeines Gesetz in der Gestaltung der Flussbetten." Bull. Acad. St. Petersbourg, ii. (1860). See also Ferrel on the motion of fluids and solids relatively to the earth's surface, Camb. (Mass.) Math. Monthly, vols. i. and ii. (1859–60); Dulk, Z. Deutsch. Geol. Ges. xxxi. (1879) p. 224. The River Irtisch is said in flowing northward to have cut so much into its right bank that villages are gradually driven eastward, Demiansk having been shifted about a mile in 240 years (Nature, xv. p. 207). But this may be accounted for by local causes. See an excellent paper on this subject with special reference to the régime of some rivers in northern Germany, by F. Klockmann, Jahrb. Preuss. Geol. Landesanst. 1882; also E. Dunker, Zeitsch. für die gesammten Naturwissenschaften, 1875, p. 463; G. K. Gilbert, Amer. Journ. Sci. xxvii. (1884) p. 427.

owing to change in the ellipticity of the orbit, the earth is 14,368,200 miles nearer the sun than when at its greatest possible distance. These maxima and minima of distance occur at vast intervals of time.[15] The last considerable eccentricity took place about 200,000 years ago, and the previous one more than half a million years earlier. Since the amount of heat received by the earth from the sun is inversely as the square of the distance, eccentricity may have had in past time much effect upon the climate of the earth, as will be pointed out further on (§ 8).

§ 3. **Precession of the Equinoxes.**—If the axis of the earth were perpendicular to the plane of its orbit, there would be equal day and night all the year round. But it is really inclined from that position at an angle of 23° 27′ 21″. Hence our hemisphere is alternately presented to and turned away from the sun, and, in this way, brings the familiar alternation of the seasons. Again, were the earth a perfect sphere, of uniform density throughout, the position of its axis of rotation would not be changed by attractions of external bodies. But owing to the protuberance along the equatorial regions, the attraction chiefly of the moon and sun tends to pull the axis aside, or to make it describe a conical movement, like that of the axis of a top, round the vertical. Hence each pole points successively to different stars. This movement, called the precession of the equinoxes, in combination with another smaller movement, due to the attraction of the moon (called *nutation*), completes its cycle in 21,000 years, the annual total advance of the equinox amounting to 62″. At present the winter in the northern hemisphere coincides with the earth's nearest

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[15] See Croll's "Climate and Time," chaps. iv. xix.

approach to the sun, or *perihelion*. In 10,500 years hence it will take place when the earth is at the furthest part of its orbit from the sun, or in *aphelion*. This movement may have had great importance in connection with former secular variations in the eccentricity of the orbit (§ 8).

§ 4. **Change in the Obliquity of the Ecliptic.**—The angle at which the axis of the earth is inclined to the plane of its orbit does not remain strictly constant. It oscillates through long periods of time to the extent of about a degree and a half, or perhaps a little more, on either side of the mean. According to Dr. Croll,[16] this oscillation must have considerably affected former conditions of climate on the earth, since, when the obliquity is at its maximum, the polar regions receive about eight and a half days' more of heat than they do at present—that is, about as much heat as lat. 76° enjoys at this day. This movement must have augmented the geological effects of precession, to which reference has just been made, and which are described in § 8.

§ 5. **Stability of the Earth's Axis.**—That the axis of the earth's rotation has successively shifted, and consequently that the poles have wandered to different points on the surface of the globe, has been maintained by geologists as the only possible explanation of certain remarkable conditions of climate, which can be proved to have formerly obtained within the Arctic Circle. Even as far north as lat. 81° 45′, abundant remains of a vegetation indicative of a warm climate, and including a bed of coal 25 to 30 feet thick, have been found *in situ*.[17] It is contended that when these plants lived, the ground could not have been permanently

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[16] Croll, Trans. Geol. Soc. Glasgow, ii. 177. "Climate and Time," chap. xxv

[17] Fielden and Heer, Quart. Journ. Geol. Soc. Nov. 1877.

frozen or covered for most of the year with thick snow. In explanation of the difficulty, it has been suggested that the north pole did not occupy its present position, and that the locality where the plants occur lay in more southerly latitudes. Without at present entering on the discussion of the question whether the geological evidence necessarily requires so important a geographical change, let us consider how far a shifting of the axis of rotation has been a possible cause of change during that section of geological time for which there are records among the stratified rocks.

From the time of Laplace,[18] astronomers have strenuously denied the possibility of any sensible change in the position of the axis of rotation. It has been urged that, since the planet acquired its present oblate spheroidal form, nothing but an utterly incredible amount of deformation could overcome the greater centrifugal force of the equatorial protuberance. It is certain, however, that the axis of rotation does not strictly coincide with the principal axis of inertia. Though the angular difference between them must always have been small, we can, without having recourse to any extramundane influence, recognize two causes which, whether or not they may suffice to produce any change in the position of the main axis of inertia, undoubtedly tend to do so. In the first place, a widespread upheaval or depression of certain unsymmetrically arranged portions of the surface to a considerable amount would tend to shift that axis. In the second place, an analogous result might arise from the denudation of continental masses of land, and the consequent filling up of sea-basins. Lord Kelvin (Sir William Thomson) freely concedes the physical

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[18] Mécanique Céleste," tome v. p. 14.

possibility of such changes. "We may not merely admit," he says, "but assert as highly probable, that the axis of maximum inertia and axis of rotation, always very near one another, may have been in ancient times very far from their present geographical position, and may have gradually shifted through 10, 20, 30, 40, or more degrees, without at any time any perceptible sudden disturbance of either land or water."[19] But though, in the earlier ages of the planet's history, stupendous deformations may have occurred, and the axis of rotation may have often shifted, it is only the alterations which can possibly have occurred during the accumulation of the stratified rocks, that need to be taken into account in connection with the evidence of changes of climate during geological history. If it can be shown, therefore, that the geographical revolutions necessary to shift the axis are incredibly stupendous in amount, improbable in their distribution, and not really demanded by geological evidence, we may reasonably withhold our belief from this alleged cause of the changes of climate during the periods of time embraced by geological records.

It has been estimated by Lord Kelvin "that an elevation of 600 feet, over a tract of the earth's surface 1000 miles square and 10 miles in thickness, would only alter the position of the principal axis by one-third of a second, or 34 feet."[20] Professor George Darwin has shown that, on the supposition of the earth's complete rigidity, no redistribution of matter in new continents could ever shift the pole from its primitive position more than 3°, but that, if its degree of rigidity is consistent with a periodical readjust-

[19] Brit. Assoc. Rep. (1876), Sections, p. 11.
[20] Trans. Geol. Soc. Glasgow, iv. p. 313. The situation of the supposed area of upheaval on the earth's surface is not stated.

ment to a new form of equilibrium, the pole may have wandered some 10° or 15° from its primitive position, or have made a smaller excursion and returned to near its old place. In order, however, that these maximum effects should be produced, it would be necessary that each elevated area should have an area of depression corresponding in size and diametrically opposite to it, that they should lie on the same complete meridian, and that they should both be situated in lat. 45°. With all these coincident favorable circumstances, an effective elevation of $\frac{1}{800}$ of the earth's surface to the extent of 10,000 feet would shift the pole $11\frac{1}{3}'$; a similar elevation of $\frac{1}{20}$ would move it $1° 46\frac{1}{2}'$; of $\frac{1}{10}$, $3° 17'$; and of $\frac{1}{2}$, $8° 4\frac{1}{2}'$. Mr. Darwin admits these to be superior limits to what is possible, and that, on the supposition of intumescence or contraction under the regions in question, the deflection of the pole might be reduced to a quite insignificant amount.[21]

Under the most favorable conditions, therefore, the possible amount of deviation of the pole from its first position would appear to have been too small to have seriously influenced the climates of the globe within geological history. If we grant that these changes were cumulative, and that the superior limit of deflection was reached only after a long series of concurrent elevations and depressions, we must suppose that no movements took place elsewhere to counteract the effect of those about lat. 45° in the two hemispheres. But this is hardly credible. A glance at a geographical globe suffices to show how large a mass of land exists now both to the north and south of that latitude, especially in the northern hemisphere, and that the deepest parts of the ocean are not antipodal to the greatest heights

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[21] Phil. Trans. Nov. 1876.

of the land. These features of the earth's surface are of old standing. There seems, indeed, to be no geological evidence in favor of any such geographical changes as could have produced even the comparatively small displacement of the axis considered possible by Professor Darwin.

In an ingenious suggestion, Sir John Evans contended that, even without any sensible change in the position of the axis of rotation of the nucleus of the globe, there might be very considerable changes of latitude due to disturbance of the equilibrium of the outer portion or shell by the upheaval or removal of masses of land between the equator and the poles, and to the consequent sliding of the shell over the nucleus until the equilibrium was restored.[22] Subsequently he precisely formulated his hypothesis as a question to be determined mathematically;[23] and the solution of the problem was worked out by the Rev. J. F. Twisden, who arrived at the conclusion that even the large amount of geographical change postulated by Dr. Evans could only displace the earth's axis of figure to the extent of less than 10′ of angle, that a displacement of as much as 10° or 15° could be effected only if the heights and depths of the areas elevated and depressed exceeded by many times the heights of the highest mountains, that under no circumstances could a displacement of 20° be effected by a transfer of matter of less amount than about a sixth part of the whole equatorial bulge, and that even this extreme amount would not necessarily alter the position of the axis of figure.[24]

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[22] Proc. Roy. Soc. xv. (1867), p. 46. [23] Q. J. Geol. Soc. xxxii. (1876), p. 62.
[24] Q. J. Geol. Soc. xxxiv. (1878), p. 41. See also E. Hill, Geol. Mag. v. (2d ser.) pp. 262, 479. O. Fisher, op. cit. pp. 291, 551.

Against any hypothesis which assumes a thin crust inclosing a liquid or viscous interior, weighty and, indeed, insuperable objections have been urged. It has been suggested, however, that the almost universal traces of present or former volcanic action, the evidence from the compressed strata in mountain regions that the crust of the earth must have a capacity for slipping toward certain lines, the great amount of horizontal compression of strata which can be proved to have been accomplished, and the secular changes of climate—notably the former warm climate near the north pole—furnish grounds for inquiry whether the doctrine of a fluid substratum over a rigid nucleus, which has been urged by several able writers, would not be compatible with mechanical considerations, and whether, under these circumstances, changes in latitude would not result from unequal thickening of the crust.[25] This question of the internal condition of the globe is discussed at p. 89.

§ 6. **Changes of the Earth's Centre of Gravity.**—If the centre of gravity in our planet, as pointed out by Herschel, be not coincident with the centre of figure, but lies somewhat to the south of it, any variation in its position will affect the ocean, which of course adjusts itself in relation to the earth's centre of gravity. How far any redistribution of the matter within the earth, in such a way as to affect the present equilibrium, is now possible, we cannot tell. But certain revolutions at the surface may from time to time produce changes of this kind. The accumulation of ice which, as will be immediately described (§ 8), is believed to gather round one pole during the maximum

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[25] O. Fisher, Geol. Mag. 1878, p. 552, "Physics of the Earth's Crust," 1882; 2d Edition 1889.

of eccentricity, will displace the centre of gravity, and, as the result of this change, will raise the level of the ocean in the glacial hemisphere.[26] The late Dr. Croll estimated that, if the present mass of ice in the southern hemisphere is taken at 1000 feet thick extending down to lat. 60°, the transference of this mass to the northern hemisphere would raise the level of the sea 80 feet at the north pole. Other methods of calculation give different results. Mr. Heath put the rise at 128 feet; Archdeacon Pratt made it more; while the Rev. O. Fisher gave it at 409 feet.[27] Subsequently, in returning to this question, Dr. Croll remarked "that the removal of two miles of ice from the Antarctic continent [and at present the mass of ice there is probably thicker than that] would displace the centre of gravity 190 feet, and the formation of a mass of ice equal to the one-half of this, on the Arctic regions, would carry the centre of gravity 95 feet further; giving in all a total displacement of 285 feet, thus producing a rise of level at the north pole of 285 feet, and in the latitude of Edinburgh of 234 feet." A very considerable additional displacement would arise from the increment of water to the mass of the ocean by the melting of the ice. Supposing half of the two miles of Antarctic ice to be replaced by an ice-cap of similar extent and one mile thick in the northern hemisphere, the other half being melted into water and increasing the mass of the ocean, Dr. Croll estimated that from this source an extra rise of 200 feet would take place in the general ocean level, so that there would be a rise of 485 feet at the north

[26] Adhemar, "Révolutions de la Mer," 1840.

[27] Croll, in Reader for 2d September, 1865, and Phil. Mag. April, 1866; Heath, Phil. Mag. April, 1869; Pratt, Phil. Mag. March, 1866; Fisher, Reader, 10th February, 1866.

pole, and 434 feet in the latitude of Edinburgh.[28] An intermittent submergence and emergence of the low polar lands might be due to the alternate shifting of the centre of gravity.

To what extent this cause has actually come into operation in past time cannot at present be determined. It has been suggested that the "raised beaches," shore-lines (*strand-linien*), or old sea-terraces, so numerous at various heights in the northwest of Europe, might be due to the transference of the oceanic waters, and not to any subterranean movement, as generally believed. Had they been due to such a general cause, they ought to have shown evidence of a gradual and uniform decline in elevation from north to south, with only such local variations as might be accounted for by the influence of masses of high land or other local cause. No such feature, however, has been satisfactorily established.[29] On the contrary, the levels of the terraces vary within comparatively short distances. Though numerous on both sides of Scotland, they disappear further north among the Orkney and Shetland islands, although these localities were admirably adapted for their formation and preservation.[30] The conclusion may be drawn that the "raised beaches" cannot be adduced as evidence of changes of the earth's centre of gravity, but are due to local and irregularly acting causes. (See Book III. Part I. Section iii. § 1, where this subject is more fully discussed.)

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[28] Croll, Geol. Mag. new series, i. (1874), p. 347; "Climate and Time," chaps. xxiii. and xxiv. and postea, p. 286. Consult also Fisher, Phil. Mag. xxxiv. (October, 1892), p. 337.

[29] The student ought, however, to consult Prof. Suess' Antlitz der Erde for the arguments in favor of an opposite opinion.

[30] Nature, xvi. (1877), p. 415.

§ 7. **Results of the Attractive Influence of Sun and Moon on the Geological Condition of the Earth.**—Many speculations have been offered to account for supposed former greater intensity of geological activity on the surface of the globe. Two causes for such greater intensity may be adduced. In the first place, if the earth has cooled down from an original molten condition, it has lost, in cooling, a vast amount of potential geological energy. It does not necessarily follow, however, that the geological phenomena resulting from internal temperature have, during the time recorded in the accessible part of the earth's crust, been steadily decreasing in magnitude. We might, on the contrary, contend that the increased resistance of a thickening cooled crust may rather have hitherto intensified the manifestations of subterranean activity, by augmenting the resistance to be overcome. In the second place, the earth may have been once more powerfully affected by external causes, such as the greater heat of the sun, and the greater proximity of the moon. That the formerly larger amount of solar heat received by the surface of our planet must have produced warmer climates and more rapid evaporation, with greater rainfall and the important chain of geological changes which such an increase would introduce, appears in every way probable, though the geologist has not yet been able to observe any indisputable indication of such a former intensity of superficial changes.

Prof. Darwin, in investigating the bodily tides of viscous spheroids, has brought forward some remarkable results bearing on the question of the possibility that geological operations, both internal and superficial, may have been once greatly more gigantic and rapid than they are now.[31]

[31] Phil. Trans. 1879, parts i. and ii.

He assumes the earth to be a homogeneous spheroid and to have possessed a certain small viscosity,[32] and he calculates the internal tidal friction in such a mass exposed to the attraction of moon and sun, and the consequences which these bodily tides have produced. He finds that the length of our day and month have greatly increased, that the moon's distance has likewise augmented, that the obliquity of the ecliptic has diminished, that a large amount of hypogene heat has been generated by the internal tidal friction, and that these changes may all have transpired within comparatively so short a period (57,000,000 years) as to place them quite probably within the limits of ordinary geological history. According to his estimate, 46,300,000 years ago the length of the sidereal day was fifteen and a half hours, the moon's distance in mean radii of the earth was 46·8 as compared with 60·4 at the present time. But 56,810,000 years back, the length of a day was only 6¾ hours, or less than a quarter of its present value, the moon's distance was only nine earth's radii, while the lunar month lasted not more than about a day and a half (1·58), or $\frac{1}{17}$ of its present duration. He arrives at the deduction that the energy lost by internal tidal friction in the earth's mass is converted into heat at such a rate that the amount lost during 57,000,000 years, if it were all applied at once, and if the earth had the specific heat of iron, would raise the temperature of the whole planet's mass 1,760° Fahrenheit, but that the distribution of this heat-generation has been such as not to interfere

[32] The degree of viscosity assumed is such that "thirteen and a half tons to the square inch acting for twenty-four hours on a slab an inch thick displaces the upper surface relatively to the lower through one-tenth of an inch. It is obvious," says Mr. Darwin, "that such a substance as this would be called a solid in ordinary parlance, and in the tidal problem this must be regarded as a very small viscosity." Op. cit. p. 531.

with the normal augmentation of temperature downward due to secular cooling, and the conclusion drawn therefrom by Sir William Thomson. Mr. Darwin further concludes from his hypothesis that the ellipticity of the earth's figure having been continually diminishing, "the polar regions must have been ever rising and the equatorial ones falling, though as the ocean followed these changes, they might quite well have left no geological traces. The tides must have been very much more frequent and larger, and accordingly the rate of oceanic denudation much accelerated. The more rapid alternation of day and night[33] would probably lead to more sudden and violent storms, and the increased rotation of the earth would augment the violence of the trade-winds, which in their turn would affect oceanic currents." [34] As above stated, no facts yet revealed by the geological record compel the admission of more violent superficial action in former times than now. But though the facts do not of themselves lead to such an admission, it is proper to inquire whether any of them are hostile to it. It will be shown in Book VI. that even as far back as early Palæozoic times, that is, as far into the past as the history of organized life can be traced, sedimentation took place very much as it does now. Sheets of fine mud and silt were pitted with rain drops, ribbed with ripple-marks, and furrowed by crawling worms, exactly as they now are on the shores of any modern estuary. These surfaces were quietly buried under succeeding sediment of a similar kind, and this for hundreds and thousands of feet. Nothing indicates violence; all the evidence favors tranquil deposit.[35] If, there-

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[33] According to his calculation, the year 57,000,000 of years ago contained 1300 days instead of 365.

[34] Op. cit. p. 532.

[35] Sir R. Ball (Nature, xxv. 1881, pp. 79, 103), starting from Prof. Darwin's

fore, Mr. Darwin's hypothesis be accepted, we must conclude either that it does not necessarily involve such violent superficial operations as he supposes, or that even the oldest sedimentary formations do not date back to a time when the influence of increased rotation could make itself evident in sedimentation, that is to say, on Mr. Darwin's hypothesis, the most ancient fossiliferous rocks cannot be as much as 57,000,000 years old.

§ 8. **Climate in its Geological Relations.**—In subsequent parts of this work data will be given from which we learn that the climates of the earth have formerly been considerably different from those which at present prevail. A consideration of the history of the solar system would of itself suggest the inference that, on the whole, the climates of early geological periods must have been warmer. The sun's heat was greater, probably the amount of it received by the earth was likewise greater, while there would be for some time a sensible influence of the planet's own internal heat upon the general temperature of the whole globe.[36] Although arguments based upon the probable climatal necessities of extinct species and genera of plants and animals

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data, pushed his conclusions to such an extreme as to call in the agency of tides more than 600 feet high in early geological times. In repudiating this application of his results, Mr. Darwin (Nature, xxv. p. 213) employs the argument I have here used from the absence of any evidence of such tidal action in the geological formations, and from the indication, on the contrary, of tranquil deposit.

[36] Lord Kelvin (Sir William Thomson) believes that the hypothesis that terrestrial temperature was formerly higher by reason of a hotter sun "is rendered almost infinitely probable by independent physical evidence and mathematical calculation." (Trans. Geol. Soc. Glasgow, v. p. 238.) Prof. Tait, however, has suggested, that the former greater heat of the sun may have raised such vast clouds of absorbing vapor round that luminary as to prevent the effective amount of radiation of heat to the earth's surface from being greater than at present; while on the other hand, a similar supposition may be made with reference to the greater amount of vapor which increased solar radiation would raise to be condensed in the earth's atmosphere. "Recent Advances in Physical Science," 1876, p. 174.

must be used with extreme caution, it may be asserted with some confidence that from the vast areas over which Palæozoic mollusks have been traced, alike in the eastern and the western hemispheres, the climates of the globe in Palæozoic time were probably more uniform than they now are. There appears to have been a gradual lowering of the general temperature during past geological time, accompanied by a tendency toward greater extremes of climate. But there are proofs also that at longer or shorter intervals cold cycles have intervened. The Glacial Period, for example, preceded our own time, and in successive geological formations indications, of more or less value, have been found that suggest if they do not prove a former prevalence of ice in what are now temperate regions.[37]

Various theories have been proposed in explanation of such alternations of climate. Some of these have appealed to a change in the position of the earth's axis relatively to the mass of the planet (*ante*, § 5). Others have been based on the notion that the earth may have passed through hot and cold regions of space. Others, again, have called in the effects of terrestrial changes, such as the distribution of land and sea, on the assumption that elevation of land about the poles must cool the temperature of the globe, while elevation round the equator would raise it.[38] But the changes of temperature appear to have affected the whole of the earth's surface, while there is not only no proof of any such enormous vicissitudes in physical geography as would be required, but good grounds for believing that the present ter-

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[37] Consult a suggestive paper by the late Dr. M. Neumayr, Nature, xlii. (1890) p. 148.

[38] In Lyell's "Principles of Geology," this doctrine of the influence of geographical changes is maintained.

restrial and oceanic areas have remained, on the whole, on the same sites from very early geological time. Moreover, as evidence has accumulated in favor of periodic alternations of climate, the conviction has been strengthened that no mere local changes could have sufficed, but that secular variations in climate must be assigned to some general and probably recurring cause.

By degrees, geologists accustomed themselves to the belief that the cold of the Glacial Period was not due to mere terrestrial changes, but was to be explained somehow as the result of cosmical causes. Of various suggestions as to the probable nature and operation of these causes, one deserves careful consideration — change in the eccentricity of the earth's orbit. Sir John Herschel[39] pointed out many years ago that the direct effect of a high condition of eccentricity is to produce an unusually cold winter, followed by a correspondingly hot summer, in the hemisphere whose winter occurs in aphelion, while an equable condition of climate at the same time prevails on the opposite hemisphere. But both hemispheres must receive precisely the same amount of solar heat, because the deficiency of heat, resulting from the sun's greater distance during one part of the year, is exactly compensated by the greater length of that season. Sir John Herschel even considered that the direct effects of eccentricity must thus be nearly neutralized.[40] As a like verdict was afterward given by Arago, Humboldt, and others, geologists were satisfied that no important change of climate could be attributed to change of eccentricity.

The late Dr. James Croll, as far back as the year 1864,

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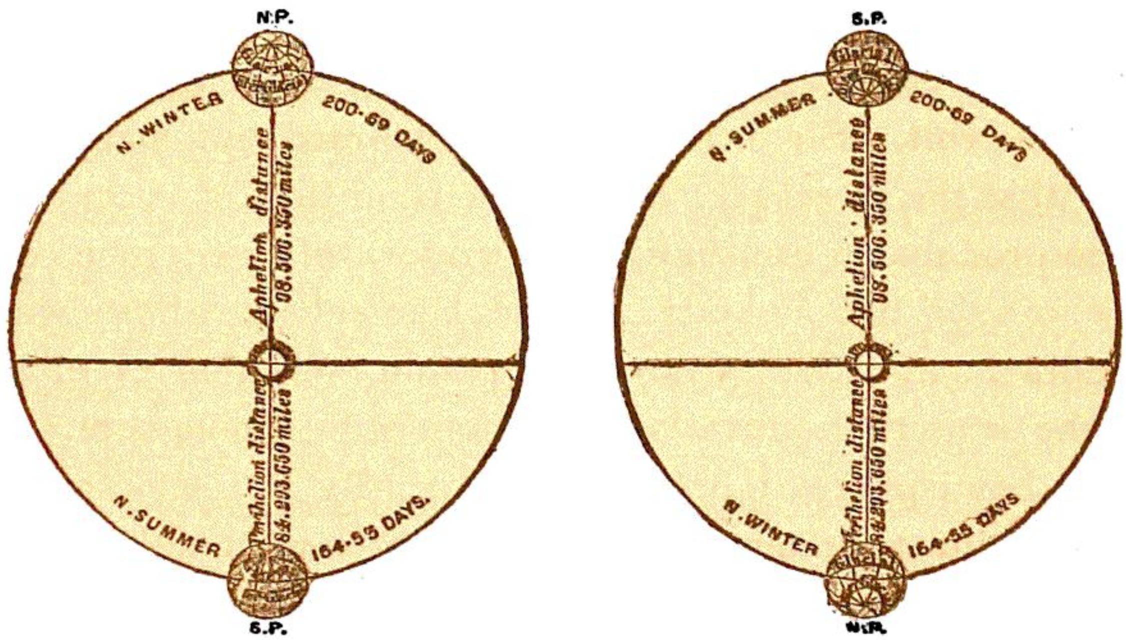
[39] Trans. Geol. Soc. vol. iii. p. 293 (2d series).

[40] "Cabinet Cyclopædia," sec. 315; "Outlines of Astronomy," sec. 368.

made an important suggestion in this matter, and subsequently worked out an elaborate development of the whole subject of the physical causes on which climate depends.[41] He was good enough to draw up the following abstract of them for former editions of the present work.

"Assuming the mean distance of the sun to be 92,400,000 miles, then when the eccentricity is at its superior limit, ·07775, the distance of the sun from the earth, when the latter is in the aphelion of its orbit, is no less than 99,584,100 miles, and when in the perihelion it is only 85,215,900 miles. The earth is, therefore, 14,368,200 miles further from the sun in the former than in the latter position. The direct



N. Winter Solstice in Aphelion *N. Winter Solstice in Perihelion*

Fig. 1.—Eccentricity of the Earth's Orbit in Relation to Climate

heat of the sun being inversely as the square of the distance, it follows that the amount of heat received by the earth in these two positions will be as 19 to 26. The present eccentricity being ·0168, the earth's distance during our northern winter is 90,847,680 miles. Suppose now that, from the precession of the equinoxes, winter in our northern hemisphere should happen when the earth is in the aphelion of its orbit, at the time that the orbit is at its greatest eccen-

[41] Phil. Mag. xxviii. (1864), p. 121. His researches will be found in detail in his volume "Climate and Time," 1875, and his later work "Discussions on Climate and Cosmology."

tricity; the earth would then be 8,736,420 miles further from the sun in winter than it is at present. The direct heat of the sun would therefore, during winter, be one-fifth less and during summer one-fifth greater than now. This enormous difference would necessarily affect the climate to a very great extent. Were the winters under these circumstances to occur when the earth was in the perihelion of its orbit, the earth would then be 14,368,200 miles nearer the sun in winter than in summer. In this case the difference between winter and summer in our latitudes would be almost annihilated. But as the winters in the one hemisphere correspond with the summers in the other, it follows that while the one hemisphere would be enduring the greatest extremes of summer heat and winter cold, the other would be enjoying perpetual summer.

"It is quite true that, whatever may be the eccentricity of the earth's orbit, the two hemispheres must receive equal quantities of heat per annum; for proximity to the sun is exactly compensated by the effect of swifter motion. The total amount of heat received from the sun between the two equinoxes is, therefore, the same in both halves of the year, whatever the eccentricity of the earth's orbit may be. For example, whatever extra heat the southern hemisphere may at present receive per day from the sun during its summer months, owing to greater proximity to the sun, is exactly compensated by a corresponding loss arising from the shortness of the season; and, on the other hand, whatever deficiency of heat we in the northern hemisphere may at present have per day during our summer half-year, in consequence of the earth's distance from the sun, is also exactly compensated by a corresponding length of season.

"It is well known, however, that those simple changes in the summer and winter distances would not alone produce a glacial epoch, and that physicists, confining their attention to the purely astronomical effects, were perfectly correct in affirming that no increase of eccentricity of the earth's orbit could account for that epoch. But the important fact was overlooked that, although the glacial epoch could not result directly from an increase of eccentricity, it might nevertheless do so indirectly from physical agents that were brought into operation as a result of an increase of eccentricity. The following is an outline of what these physical agents were, how they were brought into operation, and the way in which they may have led to the glacial epoch.

"With the eccentricity at its superior limit and the winter occurring in the aphelion, the earth would, as we have seen, be 8,736,420 miles further from the sun during that season than at present. The reduction in the amount of heat received from the sun, owing to his increased distance, would lower the midwinter temperature to an enormous extent. In temperate regions the greater portion of the moisture of the air is at present precipitated in the form of rain, and the very small portion which falls as snow disappears in the course of a few weeks at most. But in the circumstances under consideration, the mean winter-temperature would be lowered so much below the freezing-point that what now falls as rain during that season, would then fall as snow. This is not all; the winters would then not only be cooler than now, but they would also be much longer. At present the winters are nearly eight days shorter than the summers; but with the eccentricity at its superior limit and the winter solstice in aphelion, the length of the winters would exceed that of the summers by no fewer than thirty-six days. The lowering of the temperature and the lengthening of the winter would both tend to the same effect, viz. to increase the amount of snow accumulated during the winter; for, other things being equal, the longer the snow-accumulating period, the greater the accumulation. It may be remarked, however, that the absolute quantity of heat received during winter is not affected by the decrease in the sun's heat, for the additional length of the season compensated for this decrease.[42] As regards the absolute amount of heat received, increase of the sun's distance and lengthening of the winter are compensatory, but not so in regard to the amount of snow accumulated. The consequence of this state of things would be that, at the commencement of the short summer, the ground would be covered with the winter's accumulation of snow. Again, the presence of so much snow would lower the summer temperature, and prevent to a great extent the melting of the snow.

"There are three separate ways whereby accumulated masses of snow and ice tend to lower the summer temperature, viz.:

"*First*, By means of direct radiation. No matter what the intensity of the sun's rays may be, the temperature of

[42] When the eccentricity is at its superior limit, the absolute quantity of heat received by the earth during the year is, however, about one three-hundredth part greater than at present. But this does not affect the question at issue.

snow and ice can never rise above 32°. Hence, the presence of snow and ice tends by direct radiation to lower the temperature of all surrounding bodies to 32°. In Greenland, a country covered with snow and ice, the pitch has been seen to melt on the side of a ship exposed to the direct rays of the sun, while at the same time the surrounding air was far below the freezing-point; a thermometer exposed to the direct radiation of the sun has been observed to stand above 100°, while the air surrounding the instrument was actually 12° below the freezing-point. A similar experience has been recorded by travellers on the snow-fields of the Alps. These results, surprising as they no doubt appear, are what we ought to expect under the circumstances. Perfectly dry air seems to be nearly incapable of absorbing radiant heat. The entire radiation passes through it almost without any sensible absorption. Consequently the pitch on the side of the ship may be melted, or the bulb of the thermometer raised to a high temperature by the direct rays of the sun, while the surrounding air remains intensely cold. The air is cooled by *contact* with the snow-covered ground, but is not heated by the radiation from the sun.

"When the air is charged with aqueous vapor, a similar cooling effect also takes place, but in a slightly different way. Air charged with aqueous vapor is a good absorber of radiant heat, but it can only absorb those rays which agree with it in *period*. It so happens that rays from snow and ice are, of all others, those which it absorbs best. The humid air will absorb the total radiation from the snow and ice, but it will allow the greater part of, if not nearly all, the sun's rays to pass unabsorbed. But during the day, when the sun is shining, the radiation from the snow and ice to the air is negative; that is, the snow and ice cool the air by radiation. The result is, the air is cooled by radiation from the snow and ice (or rather, we should say, *to* the snow and ice) more rapidly than it is heated by the sun; and as a consequence, in a country like Greenland, covered with an icy mantle, the temperature of the air, even during summer, seldom rises above the freezing-point. Snow is a good reflector, but as simple reflection does not change the character of the rays, they would not be absorbed by the air, but would pass into stellar space. Were it not for the ice, the summers of North Greenland, owing to the continuance of the sun above the horizon, would be as warm as those of England; but instead of this, the Greenland summers are colder than our winters. Cover India with an ice sheet, and its summers would be colder than those of England.

"*Second*, Another cause of the cooling effect is that the rays which fall on snow and ice are to a great extent reflected back into space. But those that are not reflected, but absorbed, do not raise the temperature, for they disappear in the mechanical work of melting the ice. For whatsoever may be the intensity of the sun's heat, the surface of the ground will be kept at 32° so long as the snow and ice remain unmelted.

"*Third*, Snow and ice lower the temperature by chilling the air and condensing the vapor into thick fogs. The great strength of the sun's rays during summer, due to his nearness at that season, would, in the first place, tend to produce an increased amount of evaporation. But the presence of snow-clad mountains and an icy sea would chill the atmosphere and condense the vapor into thick fogs. The thick fogs and cloudy sky would effectually prevent the sun's rays from reaching the earth, and the snow, in consequence, would remain unmelted during the entire summer. In fact, we have this very condition of things exemplified in some of the islands of the Southern Ocean at the present day. Sandwich Land, which is in the same parallel of latitude as the north of Scotland, is covered with ice and snow the entire summer; and in the island of South Georgia, which is in the same parallel as the centre of England, the perpetual snow descends to the very sea-beach. Captain Sir James Ross found the perpetual snow at the sea-level at Admiralty Inlet, South Shetland, in lat. 64°; and while near this place the thermometer in the very middle of summer fell at night to 23° F. The reduction of the sun's heat and lengthening of the winter, which would take place when the eccentricity is near to its superior limit and the winter in aphelion, would in this country produce a state of things perhaps as bad as, if not worse than, that which at present exists in South Georgia and South Shetland.

"The cause which above all others must tend to produce great changes of climate, is the deflection of great ocean currents. A high condition of eccentricity tends, we have seen, to produce an accumulation of snow and ice on the hemisphere whose winters occur in aphelion. The accumulation of snow, in turn, tends to lower the summer temperature, cut off the sun's rays, and retard the melting of the snow.

In short, it tends to produce, on that hemisphere, a state of glaciation. Exactly opposite effects take place on the other hemisphere, which has its winter in perihelion. There the shortness of the winters, combined with the high temperature arising from the nearness of the sun, tends to prevent the accumulation of snow. The general result is that the one hemisphere is cooled and the other heated. This state of things now brings into play the agencies which lead to the deflection of the Gulf Stream and other great ocean currents.

"Owing to the great difference between the temperature of the equator and the poles, there is a constant flow of air from the poles to the equator. It is to this that the trade-winds owe their existence. Now, as the strength of these winds will, as a general rule, depend upon the difference of temperature that may exist between the equator and higher latitudes, it follows that the trades on the cold hemisphere will be stronger than those on the warm. When the polar and temperate regions of the one hemisphere are covered to a large extent with snow and ice, the air, as we have just seen, is kept almost at the freezing-point during both summer and winter. The trades on that hemisphere will, of necessity, be exceedingly powerful; while on the other hemisphere, where there is comparatively little snow or ice, and the air is warm, the trades will consequently be weak. Suppose now the northern hemisphere to be the cold one. The northeast trade-winds of this hemisphere will far exceed in strength the southeast trade-winds of the southern hemisphere. The *median line* between the trades will consequently lie to a very considerable distance to the south of the equator. We have a good example of this at the present day. The difference of temperature between the two hemispheres at present is but trifling to what it would be in the case under consideration; yet we find that the southeast trades of the Atlantic blow with greater force than the northeast trades, sometimes extending to 10° or 15° N. lat., whereas the northeast trades seldom blow south of the equator. The effect of the northern trades blowing across the equator to a great distance will be to impel the warm water of the tropics over into the Southern Ocean. But this is not all; not only would the median line of the trades be shifted southward, but the great equatorial currents of the globe would also be shifted southward.

"Let us now consider how this would affect the Gulf

Stream. The South American continent is shaped somewhat in the form of a triangle, with one of its angular corners, called Cape St. Roque, pointing eastward. The equatorial current of the Atlantic impinges against this corner; but as the greater portion of the current lies a little to the north of the corner, it flows westward into the Gulf of Mexico and forms the Gulf Stream. A considerable portion of the water, however, strikes the land to the south of the cape, and is deflected along the shore of Brazil into the Southern Ocean, forming what is known as the Brazilian current. Now, it is obvious that the shifting of the equatorial current of the Atlantic only a few degrees to the south of its present position—a thing which would certainly take place under the conditions which we have been detailing—would turn the entire current into the Brazilian branch, and instead of flowing chiefly into the Gulf of Mexico, as at present, it would all flow into the Southern Ocean, and the Gulf Stream would consequently be stopped. The stoppage of the Gulf Stream, combined with all those causes which we have just been considering, would place Europe under a glacial condition, while at the same time the temperature of the Southern Ocean would, in consequence of the enormous quantity of warm water received, have its temperature (already high from other causes) raised enormously. And what holds true in regard to the currents of the Atlantic holds also true, though perhaps not to the same extent, of the currents of the Pacific.

"If the breadth of the Gulf Stream be taken at 50 miles, its depth at 1000 feet, its mean velocity at 2 statute miles an hour, the temperature of the water when it leaves the gulf at 65°, and the return current at 40° F.,[43] then, the quantity of heat conveyed into the Atlantic by this stream is equal to one-fourth of all the heat received from the sun by that ocean from the Tropic of Cancer to the Arctic Circle.[44] From principles discussed at considerable length

[43] Sir Wyville Thomson states that in May, 1873, the "Challenger" expedition found the Gulf Stream, at the point where it was crossed, to be about sixty miles in width, 100 fathoms deep, and flowing at the rate of three knots per hour. This makes the volume of the stream one-fifth greater than the above estimate.

[44] The quantity of heat conveyed by the Gulf Stream for distribution is equal to 77,479,650,000,000,000,000 foot-pounds per day. The quantity received from the sun by the North Atlantic is 310,923,000,000,000,000,000 foot-pounds. "Climate and Time," chap. ii.

in 'Climate and Time' it is shown that, but for the Gulf Stream and other currents, London would have a mean annual temperature 40° lower than at present.

"But there is still another cause which must be noticed —a strong undercurrent of air *from* the north implies an equally strong upper current *to* the north. Now if the effect of the undercurrent would be to impel the warm water at the equator to the south, the effect of the upper current would be to carry the aqueous vapor formed at the equator to the north; the upper current, on reaching the snow and ice of temperate regions, would deposit its moisture in the form of snow; so that it is probable that, notwithstanding the great cold of the glacial epoch, the quantity of snow falling in the northern regions would be enormous. This would be particularly the case during summer, when the earth would be in the perihelion and the heat at the equator great. The equator would be the furnace where evaporation would take place, and the snow and ice of temperate regions would act as a condenser.

"The foregoing considerations, as well as many others which might be stated, lead to the conclusion that, in order to raise the mean temperature of the globe, *water* should be placed along the equator, and not *land*, as was contended by Sir Charles Lyell and others. For if land be placed at the equator, the possibility of conveying the sun's heat from the equatorial regions by means of ocean currents is prevented."[45]

The astronomical theory in explanation of former great differences of terrestrial climate has recently been illustrated and enforced by Sir Robert Ball, who, while strengthening the general arguments in its favor, especially insists upon the existence of an important law in the distribution of solar heat on the earth's surface, which he thinks has been hitherto overlooked. He remarks that the original state-

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[45] That climate, however, may be considerably affected by changes, such as are known to have taken place in the distribution of land and sea, must be frankly conceded. This has been recently cogently argued by Mr. Wallace in his "Island Life," 1880. Mr. Croll's views, summarized above, have been adversely criticised by Prof. Newcombe, for whose papers and Dr. Croll's replies see Amer. Journ. Science, 1876, 1883, 1884, and the work by the latter writer, "Discussions on Climate and Cosmology," already referred to.

ment of Sir John Herschel that the heat received by the earth from the sun is equally divided between the winter and summer seasons has given rise to an entirely erroneous impression. Although "it is certainly true that during the summer in one hemisphere the heat received on the whole earth is equal to the heat received on the whole earth during the ensuing winter on the same hemisphere," yet on any given hemisphere almost twice as much heat can be demonstrated to be received during summer as during winter.[46] The law is thus stated: "Of the total amount of heat received from the sun on a hemisphere of the earth in the course of a year, 63 per cent is received during the summer, and 37 per cent is received during the winter."[47] It is obvious that while, under the operation of this law, the total amount of heat received and the ratio of its distribution between summer and winter would remain unchanged, enormous differences in terrestrial climate might result according as the seasons varied in length with changes in the eccentricity of the orbit.

Inter-Glacial Periods.—Allusion has already been made to the accumulating evidence that changes of climate have been recurrent, and to the deduction from this alternation or periodicity that they have probably been due to some general or cosmical cause. Dr. Croll ingeniously showed that every long cold period arising in each hemisphere from the circumstances sketched in the preceding pages, must have been interrupted by several shorter warm periods.

"When the one hemisphere," he says, "is under glaciation, the other is enjoying a warm and equable climate.

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[46] "The Cause of an Ice Age," London, 1891, p. 120. [47] Ibid. p. 90.

But, owing to the precession of the equinoxes, the condition of things on the two hemispheres must be reversed every 10,000 years or so. When the solstice passes the aphelion, a contrary process commences; the snow and ice gradually begin to diminish on the cold hemisphere and to make their appearance on the other hemisphere. The glaciated hemisphere turns by degrees warmer, and the warm hemisphere colder, and this continues to go on for a period of ten or twelve thousand years, until the winter solstice reaches the perihelion. By this time the conditions of the two hemispheres have been reversed; the formerly glaciated hemisphere has now become the warm one, and the warm hemisphere the glaciated. The transference of the ice from the one hemisphere to the other continues as long as the eccentricity remains at a high value. It is probable that, during the warm inter-glacial periods, Greenland and the Arctic regions would be comparatively free from snow and ice, and enjoying a temperate and equable climate."

BOOK II

GEOGNOSY

AN INVESTIGATION OF THE MATERIALS OF THE EARTH'S SUBSTANCE

PART I.—A GENERAL DESCRIPTION OF THE PARTS OF THE EARTH

A DISCUSSION of the geological changes which our planet has undergone ought to be preceded by a study of the materials of which the planet consists. This latter branch of inquiry is termed Geognosy.

Viewed in a broad way, the earth may be considered as consisting of (1) two envelopes—an outer one of gas (atmosphere), completely surrounding the planet, and an inner one of water (hydrosphere), covering about three-fourths of the globe; and (2) a globe (lithosphere), cool and solid on its surface, but possessing a high internal temperature.

I.—*The Envelopes—Atmosphere and Hydrosphere*

It is certain that the present gaseous and liquid envelopes of the planet form only a portion of the original mass of gas and water with which the globe was invested. Fully a half of the outer shell or crust of the earth consists of oxygen, which, there can be no doubt, once existed in the atmosphere. The extent, likewise, to which water has been abstracted by minerals is almost incredible. It has been estimated that already one-third of the whole mass of the ocean has been thus absorbed. Eventually the condition of the planet will probably resemble that of the moon—a globe without air, or water, or life of any kind.

1. The Atmosphere.—The gaseous envelope to which the name of atmosphere is given, extends to a distance of perhaps 500 or 600 miles from the earth's surface, possibly in a state of extreme tenuity to a still greater height. But its thickness must necessarily vary with latitude and changes in atmospheric pressure. The layer of air lying over the poles is not so deep as that which surrounds the equator.

Many speculations have been made regarding the chemical composition of the atmosphere during former geological periods. There can indeed be no doubt that it must originally have differed very greatly from its present condition. Besides the abstraction of the oxygen which now forms fully a half of the outer crust of the earth, the vast beds of coal found all over the world, in geological formations of many different ages, doubtless represent so much carbon-dioxide (carbonic acid) once present in the air. According to Sterry Hunt, the amount of carbonic acid absorbed in the process of rock-decay, and now represented in the form of carbonates in the earth's crust, probably equals two hundred times the present volume of the entire atmosphere.[1] The chlorides in the sea, likewise, were probably carried down out of the atmosphere in the primitive condensation of aqueous vapor. It has often been stated that, during the Carboniferous period, the atmosphere must have been warmer and with more aqueous vapor and carbon-dioxide in its composition than at the present day, to admit of so luxuriant a flora as that from which the coal-seams were formed. There seems, however, to be at present no method of arriving at any certainty on this subject.

[1] Brit. Assoc. Rep. 1878, Sects. p. 544.

As now existing, the atmosphere is considered to be normally a mechanical mixture of nearly 4 volumes of nitrogen and 1 of oxygen (N79·4, O20·6), with minute proportions of carbon-dioxide and water-vapor and still smaller quantities of ammonia and the powerful oxidizing agent, ozone. These quantities are liable to some variation according to locality. The mean proportion of carbon-dioxide is about 3·5 parts in every 10,000 of air. In the air of streets and houses the proportion of oxygen diminishes, while that of carbon-dioxide increases. According to the researches of Angus Smith, very pure air should contain not less than 20·99 per cent of oxygen, with 0·030 of carbon-dioxide; but he found impure air in Manchester to have only 20·21 of oxygen, while the proportion of carbon-dioxide in that city during fog was ascertained to rise sometimes to 0·0679, and in the pit of the theatre to the very large amount of 0·2734. As plants absorb carbon-dioxide during the day and give it off at night, the quantity of this gas in the atmosphere oscillates between a maximum at night and a minimum during the day. During the part of the year when vegetation is active, it is believed that there is at least 10 per cent more carbonic acid in the air of the open country at night than in the day.[2] Small as the normal percentage of this gas in the air may seem, yet the total amount of it in the whole atmosphere probably exceeds what would be disengaged if all the vegetable and animal matter on the earth's surface were burned.

The other substances in the air are gases, vapors, and solid particles. Of these by much the most important is the vapor of water, which is always present, but

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[2] Prof. G. F. Armstrong. Proc. Roy. Soc. xxx. (1880), p. 343.

in very variable amount according to temperature.[3] It is this vapor which chiefly absorbs radiant heat.[4] It condenses into dew, rain, hail, and snow. In assuming a visible form, and descending through the atmosphere, it takes up a minute quantity of air, and of the different substances which the air may contain. Being caught by the rain, and held in solution or suspension, these substances can be best examined by analyzing rain-water. In this way, the atmospheric gases, ammonia, nitric, sulphurous, and sulphuric acids, chlorides, various salts, solid carbon, inorganic dust, and organic matter have been detected. The fine microscopic dust so abundant in the air is no doubt for the most part due to the action of wind in lifting up the finer particles of disintegrated rock on the surface of the land. Volcanic explosions sometimes supply prodigious quantities of fine dust. There is probably also some addition to the solid particles in the atmosphere from the explosion and dissipation of meteorites on entering our atmosphere. To the wide diffusion of minute solid particles in the air great importance in the condensation of vapor has recently been assigned. (Book III. Part II. Section ii.)

The comparatively small, but by no means unimportant, proportions of these minor components of the atmosphere are much more liable to variation than those of the more essential gases. Chloride of sodium, for instance, is, as might be expected, particularly abundant in the air bordering the sea. Nitric acid, ammonia, and sulphuric acid

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[3] A cubic metre of air at the freezing-point can hold only 4·871 grammes of water-vapor, but at 40° C. can take up 50·70 grammes. One cubic mile of air saturated with vapor at 35° C. will, if cooled to 0°, deposit upward of 140,000 tons of water as rain. Roscoe and Schorlemmer's "Chemistry," i. p. 452.

[4] See Tyndall's researches which established this important function of the aqueous vapor of the atmosphere, and their confirmation by meteorological observation. S. A. Hill, Proc. Roy. Soc. xxxiii. 216, 435.

appear most conspicuously in the air of towns. The organic substances present in the air are sometimes living germs, such as probably often lead to the propagation of disease, and sometimes mere fine particles of dust derived from the bodies of living or dead organisms.[5]

As a geological agent, the atmosphere effects changes by the chemical reactions of its constituent gases and vapors, by its varying temperature, and by its motions. Its functions in these respects are described in Book III. Part. II. Section i.

2. **The Oceans.**—Rather less than three-fourths of the surface of the globe (or about 144,712,000 square miles) are covered by the irregular sheet of water known as the Sea. Within the last twenty years, much new light has been thrown upon the depths, temperatures, and biological conditions of the ocean-basins, more particularly by the "Lightning," "Porcupine," "Challenger," "Tuscarora," "Blake," "Gazelle" and other expeditions fitted out by the British, American, German and Norwegian Governments.[6] It has been ascertained that few parts of the Atlantic Ocean exceed 3000 fathoms, the deepest sounding obtained there being one taken about 100 miles north from the island of St. Thomas, which gave 3875 fathoms, or rather less than 4½ miles. The Atlantic appears to have an average depth

[5] The air of towns is peculiarly rich in impurities, especially in manufacturing districts, where much coal is used. These impurities, however, though of serious consequence to the towns in a sanitary point of view, do not sensibly affect the general atmosphere, seeing that they are probably in great measure taken out of the air by rain, even in the districts which produce them. They possess, nevertheless, a special geological significance, and in this respect, too, have important economic bearings. See on this whole subject, Angus Smith's "Air and Rain," and the account of Rain in Book III. Part II. Sect. ii.

[6] See Wyville Thomson, "The Depths of the Sea," 1873; "The Atlantic," 1877; "Report of 'Challenger' Expedition," especially the forthcoming volumes giving a summary of results; A. Agassiz, "Three Cruises of the 'Blake,'" 1888; "Den Norske Nordhavs-Expedition," 1876–78.

in its more open parts of from 2000 to 3000 fathoms, or from about 2 to $3\frac{1}{2}$ miles. In the Pacific Ocean H.M. Ship "Challenger" got soundings of 3950 and 4475 fathoms, or about $4\frac{1}{2}$ and rather more than 5 miles. Since then the U. S. Ship "Tuscarora" obtained a still deeper sounding (4655 fathoms), to the east of the Kurile Islands. This is the deepest abyss yet found in any part of the ocean. But these appear to mark exceptionally abysmal depressions, the average depth being, as in the Atlantic, between 2000 and 3000 fathoms. We may therefore assume, as probably not far from the truth, that the average depth of the sea is about 2500 fathoms, or nearly 3 miles. Its total cubic contents will thus be about 400 millions of cubic miles.

With regard also to the form of the bottom of the great oceans, much additional information has recently been obtained. Over vast areas in the central regions, the sea-floor appears to form great plains, with comparatively few inequalities, but with lines of submarine ridges, comparable to chains of hills or mountains on the land. Recent soundings, however, taken at short distances, have revealed, in parts of the Atlantic that were supposed to be deep and with a tolerably uniform bottom, submarine peaks rising to within 50 fathoms from the surface.[7] A vast central ridge has also been traced down the length of this ocean, from which a few lonely peaks rise above sea-level—the Azores, St. Paul, Ascension, and Tristan d'Acunha. In the Pacific Ocean, the lines of coral-islands appear to rise on submarine ridges, having a general northwesterly and southeasterly trend. It is significant that the islands which thus appear far from any large mass of land are either coral-reefs

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[7] "Times," 7th Dec. 1883. [J. Y. Buchanan.]

or of volcanic origin, and contain none of the granites, schists and other ordinary continental rocks. St. Helena and Ascension in the Atlantic, and the Friendly and Sandwich Islands in the Pacific Ocean are conspicuous examples.

Another important result of recent deep-sea research is the determination of the relation of mediterranean seas to the main ocean. These basins, such as the North, Mediterranean, and Black Seas, the Gulf of Mexico, Caribbean Sea, Baffin's Bay, Hudson's Bay, Sea of Okhotsk, and Chinese Sea, belong rather to the continental than the oceanic areas of the earth's surface. An elevation of a few hundred fathoms would convert most of them into land, with here and there deep water-filled basins.

A question of high importance in geological inquiry is the form of the surface of the sea or what is usually called the sea-level. It has been generally assumed that this surface is stable and uniform and nearly that of an ellipsoid of revolution, owing its equilibrium to the force of gravity on the one hand and the centrifugal force of rotation on the other. But in recent years this conception has been called in question both by physicists and geologists. Observations as well as calculations have shown that the attraction exercised by masses of land raises the level of the adjacent sea, and attempts have been made to determine how far the deformation thus caused departs from the mean of the theoretical ellipsoid of revolution. According to Bruns, a continent may cause a difference of more than 3000 feet between the actual level of the sea and that of the ellipsoid. But the results of such calculations will greatly depend on the assumption on which they start as to the nature of the earth's crust. R. S. Woodward has calculated that if the continent of Europe and Asia be supposed to be simply a superficial aggregation of matter with a density as great as the parts under the sea, the elevation of sea-level at the centre of the continent due to attraction would amount to about 2900 feet, but that, if the continental mass be assumed to imply a defect of density underneath it, the elevation of the sea at the centre of the continent due to attraction would be only about 10 feet.[8] This subject is further considered in Book III. Part I. Section iii.

The water of the ocean is distinguished from ordinary terrestrial waters by a higher specific gravity, and the presence of so large a proportion of saline ingredients as to impart a strongly salt taste. The average density of sea-water is about 1·026, but it varies slightly in different parts even of the same ocean. According to the observations of J. Y. Buchanan during the "Challenger" expedition, some of the heaviest sea-water occurs in the pathway of the trade-winds of the North Atlantic, where evaporation must be comparatively rapid, a density of 1·02781 being registered. Where, however, large rivers enter the sea, or where there is much melting ice, the density diminishes; Buchanan found among the broken ice of the Antarctic Ocean that it had sunk to 1·02418.[9] A series of soundings taken during the "Vega" expedition in the Kara Sea (lat. 76° 18′, long. 95° 30′ E.) gave a progressive increase of salinity from 1·1 at the surface to 3·4 at 30 fathoms, the surface being freshened by the water poured into the sea by the Siberian rivers.[10]

The greater density of sea-water depends, of course,

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[8] Bruns, "Die Figur der Erde," Berlin, 1876; R. S. Woodward, Bull. U. S. Geol. Surv. No. 48, p. 85 (1888).

[9] Buchanan, Proc. Roy. Soc. (1876), vol. xxiv.

[10] O. Pettersson, "Vega-Expeditionens Vetenskapliga Iakttagelser," vol. ii. Stockholm, 1883.

upon the salts which it contains in solution. At an early period in the earth's history, the water now forming the ocean, together with the rivers, lakes and snowfields of the land, existed as vapor, in which were mingled many other gases and vapors, the whole forming a vast atmosphere surrounding the still intensely hot globe. Under the enormous pressure of the primeval atmosphere, the first condensed water might have had a temperature little below the critical one.[11] In condensing, it would carry down with it many substances in solution. The salts now present in sea-water are to be regarded as principally derived from the primeval constitution of the sea, and thus we may infer that the sea has always been salt. It is probable, however, that, as in the case of the atmosphere, the composition of the ocean-water has acquired its present character only after many ages of slow change, and the abstraction of much mineral matter originally contained in it. There is evidence, indeed, among the geological formations that large quantities of lime, silica, chlorides and sulphates have in the course of time been removed from the sea.[12]

But it is manifest also that, whatever may have been the original composition of the oceans, they have for a vast section of geological time been constantly receiving mineral matter in solution from the land. Every spring, brook and river removes various salts from the rocks over which it moves, and these substances, thus dissolved, eventually find their way into the sea. Consequently sea-water ought to contain more or less traceable proportions of every

[11] Q. J. Geol. Soc. xxxvi. (1880), pp. 112, 117. Fisher, "Physics of Earth's Crust," 2d edit. p. 148.

[12] Sterry Hunt supposed that the saline waters of North America derive their mineral ingredients from the sediments and precipitates of the sea in which the Palæozoic rocks were deposited. "Geological and Chemical Essays," p. 104.

substance which the terrestrial waters can remove from the land—in short, of probably every element present in the outer shell of the globe, for there seems to be no constituent of the earth which may not, under certain circumstances, be held in solution in water. Moreover, unless there be some counteracting process to remove these mineral ingredients, the ocean-water ought to be growing, insensibly perhaps, salter, for the supply of saline matter from the land is incessant. It has been ascertained indeed, with some approach to certainty, that the salinity of the Baltic and Mediterranean is gradually increasing.[13]

The average proportion of saline constituents in the water of the great oceans far from land is about three and a half parts in every hundred of water.[14] But in inclosed seas, receiving much fresh water, it is greatly reduced, while in those where evaporation predominates it is correspondingly augmented. Thus the Baltic water contains from one-seventh to nearly a half of the ordinary proportion in ocean-water, while the Mediterranean contains sometimes one-sixth more than that proportion. Forchhammer has shown the presence of the following twenty-seven elements in sea-water: oxygen, hydrogen, chlorine, bromine, iodine, fluorine, sulphur, phosphorus, nitrogen, carbon,

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[13] Paul, in Watts's "Dictionary of Chemistry," v. p. 1020. For a detailed study of the Eastern Mediterranean, see the Reports of a Commission, Denksch. Akad. Wiss. Vienna, 1892 *et seq.*

[14] Dittmar's elaborate researches on the samples of ocean water collected by the "Challenger" expedition show that the lowest percentage of salts obtained was 3·301, from the southern part of the Indian Ocean, south of lat. 66°, while the highest was 3·737, from the middle of the North Atlantic, at about lat. 23°. Some valuable results from observations on the waters of the North Atlantic are given by H. Tornöe and L. Schmelck in the Report of the Norwegian North-Atlantic Expedition, 1876–78. The average proportion of salts was found to be from 3·47 to 3·51 per cent, the mean quantities of each constituent as estimated being as follows: $CaCO_3$, 0·002; $CaSo_4$, 0·1395; $MgSO_4$, 0·2071; $MgCl_2$, 0·3561; KCl, 0·0747; $NaHCO_3$, 0·0166; NaCl, 2·682.

silicon, boron, silver, copper, lead, zinc, cobalt, nickel, iron, manganese, aluminium, magnesium, calcium, strontium, barium, sodium, and potassium.[15] To these may be added arsenic, lithium, cæsium, rubidium, gold, and probably most if not all of the other elements, though in proportions too minute for detection. The chief constituents have been determined by Dittmar to be present in the proportions shown in the first column of the subjoined tables. Assuming them to occur in the combinations shown in the second column, they are present in the average ratios therein stated:[16]

I		II	
Chlorine	55·292	Chloride of sodium	77·758
Bromine	0·188	Chloride of magnesium	10·887
Sulphuric acid, SO_3	6·410	Sulphate of magnesia	4·737
Carbonic acid, CO_2	0·152	Sulphate of lime	3·600
Lime, CaO	1·676	Sulphate of potash	2·465
Magnesia, MgO	6·209	Bromide of magnesium	0·217
Potash, KO	1·332	Carbonate of lime	0·345
Soda, Na_2O	41·234	Total Salts	100·000
Subtract Basic Oxygen equivalent to the Halogens	12·493		
Total Salts	100·000		

Sea-water is appreciably alkaline, its alkalinity being due to the presence of carbonates, of which carbonate of lime is one.[17] In addition to its salts it always contains dissolved

[15] Forchhammer, Phil. Trans. clv. p. 205. According to Thorpe and Morton (Chem. Soc. Journ. xxiv. p. 507), the water of the Irish Sea contains in summer rather more salts than in winter. In 1000 grammes of the summer water of the Irish Sea they found 0·04754 grammes of carbonate of lime, 0·00503 of ferrous carbonate and traces of silicic acid. For exhaustive chemical investigations regarding the chemistry of ocean-water consult Dittmar, in vol. i. "Physics and Chemistry," Report of Voyage of the "Challenger," 1884; also the "Chemistry" part of the Report of the Norwegian North-Atlantic Expedition, 1876–1878.

[16] Dittmar, op. cit. p. 203 *et seq*. For further reference to the chemistry of sea-water, especially in connection with the action of marine organisms, see *postea*, p. 484.

[17] Dittmar, op. cit. p. 206.

atmospheric gases. From the researches conducted during the voyage of the "Bonité" in the Atlantic and Indian Oceans, it was estimated that the gases in 100 volumes of sea-water ranged from 1·85 to 3·04, or from two to three per cent. From observations made during the "Porcupine" cruise of 1868, it was ascertained that the proportion of oxygen was greatest in the surface water, and least in the bottom water. The dissolved oxygen and nitrogen are doubtless absorbed from the atmosphere, the proportion so absorbed being mainly regulated by temperature. According to Dittmar's recent determinations, a litre of sea-water at 0° C. will take up 15·60 cubic centimetres of nitrogen and 8·18 of oxygen, while at 30° C. the proportions sink respectively to 8·36 and 4·17. He regards the carbonic acid as occurring chiefly as carbonates, its presence in the free state being exceptional. During the voyage of the "Challenger," Buchanan ascertained that the proportion of carbonic acid is always nearly the same for similar temperatures, the amount in the Atlantic surface water, between 20° and 25° C., being 0·0466 gramme per litre, and in the surface Pacific water 0·0268; and that sea-water contains sometimes at least thirty times as much carbonic acid as an equal bulk of fresh water would do.[18] A supposed greater proportion of carbonic acid in the deeper and colder waters of the ocean has been suggested as the main cause of the disappearance of the larger and more delicate calcareous pelagic organisms from abysmal deposits, these forms being more readily attacked and carried away in

[18] Proc. Roy. Soc. xxiv. According to Mr. Tornöe (Norwegian North-Atlantic Expedition, 1876–78, "Chemistry") most of the carbonic acid of sea-water is in combination with soda as bicarbonate of soda. See his memoir for an estimate of the proportion of air in sea-water; also J. Y. Buchanan, Nature, xxv. p. 386. Dittmar, op. cit. p. 209.

solution; but according to Dittmar, even alkaline sea-water, if given sufficient time, will take up carbonate of lime in addition to what it already contains.[19] Another of the constituents of sea-water is diffused organic matter, derived from the bodies of dead plants and animals, and no doubt of great importance as furnishing food for the lower grades of animal life.[20]

II.—*The Solid Globe or Lithosphere*

Within the atmospheric and oceanic envelopes lies the inner solid globe. The only portion of it which, rising above the sea, is visible to us, and forms what we term Land, occupies rather more than one-fourth of the total superficies of the globe, or about 52,000,000 square miles.

§ 1. **The Outer Surface.**—The land is placed chiefly in the northern hemisphere and is disposed in large masses, or continents, which taper southward to about half the distance between the equator and the south pole. No adequate cause has yet been assigned for the present distribution of the land. It can be shown, however, that portions of the continents are of extreme geological antiquity. There is reason to believe, indeed, that the present terrestrial areas have on the whole been land, or have, at least, never been submerged beneath deep water, from the time of the earliest stratified formations; and that, on the other hand, the ocean-basins have always been vast areas of depression. This subject will be discussed in subsequent pages.

In the New World, the continental trend is approxi-

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[19] Dittmar, op. cit. p. 222.

[20] Different estimates have been made of the proportion of organic matter. According to the researches of L. Schmelck (Norwegian North-Atlantic Expedition, 1876–78, Part. ix. p. 4), the proportion is 0·0025 gramme in 100 c.c. of water.

mately north and south; in the Old World, though less distinctly marked, it ranges on the whole east and west. The intimate relation which may be observed between this general trend and the direction of mountain chains, is best exhibited by the American continent. Europe and Africa may be considered as forming, with Asia, the vast continental mass of the Old World. The existing severance of Africa and Europe is of comparatively recent date. On the other hand, Europe and Asia were not always so continuous as at present. But even where the continents of the Old World are separated by sea, the intervening hollows, though now covered by ocean-water, must be regarded as essentially part of the continental areas. Asia is linked with Australia by a chain of islands. The great contrast between the Asiatic and Australian faunas, however, affords good grounds for the belief that, at least for an enormous period of time, Asia and Australia have been divided by an important barrier of sea.

While any good map of the globe enables us to see at a glance the relative positions and areas of the continents and oceans, most maps fail to furnish any data by which the general height or volume of a continent may be estimated. As a rule, the mountain-chains are exaggerated in breadth, and incorrectly indicated, while no attempt is made to distinguish between high plateaus and low plains. In North America, for example, a continuous shaded ridge is placed down the axis of the continent, and marked "Rocky Mountains," while the vast level or gently rolling prairies are left with no mark to distinguish them from the maritime plains of the Eastern and Southern States. In reality there is no such continuous mountain-chain. The so-called "Rocky Mountains" consist of many independent and sometimes widely separated ridges, having a general meridional trend, and rising above a vast plateau, which is itself 4000 or 5000 feet in elevation. It is not these intermittent ridges which really form the great mass of the land in that region, but the widely extended lofty plateau, or rather succession of plateaus, which supports them. In Europe, also, the Alps form but a subordinate part of the total bulk of the land. If their materials could be spread out over the continent, it has been calculated that they would not increase its height more than about twenty-one feet.[21]

Attempts have been made to estimate the probable average height which would be attained if the various inequalities of the land could be levelled down. Humboldt estimated the mean height of Europe to be about 671, of Asia 1132, of North America 748, and of South America 1151 feet.[22] Herschel supposed the mean height of Africa to be 1800 feet.[23] These figures, though based on the best data available at the time, are no doubt much under the truth. In particular, the average height assigned to North America is evidently far less than it should be; for the great plains west of the Mississippi Valley reach an altitude of about 5000 feet, and serve as the platform from which the mountain ranges rise. The height of Asia also is obviously

[21] M. De Lapparent ("Traité de Géologie," 3d edit. p. 57) gives the following estimate of relative heights and areas, the area below sea-level being taken as 0·6 of the whole.

Zone	I.	(from sea-level to	200 metres)	covers	34·7 %	of the terrestrial surface
"	II.	"	200 " 500	"	21·6 "	"
"	III.	"	500 " 1000	"	21·4 "	"
"	IV.	"	1000 " 2000	"	14·2 "	"
"	V.	"	2000 " 3000	"	3·7 "	"
"	VI.	"	3000 " 4000	"	2·1 "	"
"	VII.		above 4000	"	1·7 "	"
					99·4 "	"

[22] "Aise Centrale," tom. i. p. 168.

[23] "Physical Geography," p. 119.

much greater than this old estimate. G. Leipoldt has computed the mean height of Europe to be 296·838 metres (973·628 feet).[24] Prof. A. De Lapparent makes the mean height of the land of the globe 2120 feet, and estimates the mean height of Europe to be 958 feet, Asia 2884, Africa 1975, North America 1952, and South America 1762.[25] Dr. John Murray computes these heights as follows: Europe 939, Asia 3189, Africa 2021, North America 1888, South America 2078, Australia 805 feet, general mean height of land 2252 feet.[26] It is of some consequence to obtain as near an approximation to the truth in this matter as may be possible, in order to furnish a means of comparison between the relative bulk of different continents, and the amount of material on which geological changes can be effected.

The highest elevation of the surface of the land is the summit of Mount Everest, in the Himalaya range (29,000 feet); the deepest depression not covered by water is that of the shores of the Dead Sea (1300 feet below sea-level). There are, however, many subaqueous portions of the land which sink to greater depths. The bottom of the Caspian Sea, for instance, lies about 3000 feet below the general sea-level. The vertical difference between the highest point of the land and the maximum known depth of the sea is 56,932 feet or nearly 11 miles.

There are two conspicuous junction-lines of the land with its overlying and surrounding envelopes. First, with

[24] "Die Mittlere Höhe Europas," Leipzig, 1874. In this work the mean height of Switzerland is put down as 1299·91 metres; Spanish peninsula, 700·60; Austria, 517·87; Italy, 517·17; Scandinavia, 428·10; France, 393·84; Great Britain, 217·70; German Empire, 213·66; Russia, 167·09; Belgium, 163·36; Denmark (exclusive of Iceland), 35·20; the Netherlands (exclusive of Luxemburg and the tracts below sea-level), 9·61.

[25] "Traité," p. 56.

[26] Scottish Geog. Mag. iv. (1888), 23.

the Air, expressed by the contours or relief of the land. Second, with the Sea, expressed by coast-lines.

(1.) Contours or Relief of the Land.—While the surface of the land presents endless diversities of detail, its leading features may be generalized as mountains, table-lands, and plains.

Mountains.—The word "mountain" is, properly speaking, not a scientific term. It includes many forms of ground utterly different from each other in size, shape, structure, and origin. It is popularly applied to any considerable eminence or range of heights, but the height and size of the elevated ground so designated vary indefinitely. In a really mountainous country the word would be restricted to the loftier masses of ground, while such a word as hill would be given to the lesser heights. But in a region of low or gently undulating land, where any conspicuous eminence becomes important, the term mountain is lavishly used. In Eastern America this habit has been indulged in to such an extent, that what are, so to speak, mere hummocks in the general landscape, are dignified by the name of mountains.

It is hardly possible to give a precise scientific definition to a term so vaguely employed in ordinary language. When a geologist uses the word, he must either be content to take it in its familiar vague sense, or must add some phrase defining the meaning which he attaches to it. He finds that there are three leading and totally distinct types of elevation which are all popularly termed mountains. 1. Single eminences, standing alone upon a plain or table-land. This is essentially the volcanic type. The huge cones of Vesuvius, Etna, and Teneriffe, as well as the smaller ones so abundant in volcanic districts, are examples of it. There occur, however, occasional isolated eminences that stand up as remnants of once extensive rock-formations. These have no real analogy with volcanic elevations, but should be classed under the next type. The remarkable *buttes* of Western America are good illustrations of them. 2. Groups of eminences connected at the sides or base, often forming lines of ridge between divergent valleys, and owing their essential forms not to underground structure so much as to superficial erosion. Many of the more ancient uplands, both in the Old World and the New, furnish examples of this type, such as the Highlands of Scotland, the hills of Cumberland and Wales, the high grounds between Bohemia and Bavaria, the Laurentide Mountains of Canada, and the Green and White Mountains of New England. 3. Lines of lofty ridge rising into a succession of more or less distinct summits, their general external form having relation to an internal plication of their component rocks. These linear elevations, whose existence and trend have been determined immediately by subterranean movement, are the true mountain-ranges of the globe. They may be looked upon as the crests of the great waves into which the crust of the earth has been thrown. All the great mountain-lines of the world belong to this type.

Leaving the details of mountain-form to be described in Book VII., we may confine our attention here to a few of the more important general features. In elevations of the third or true mountain type, there may be either one line or range of heights, or a series of parallel and often coalescent ranges. In the Western Territories of the United States, the vast plateau has been, as it were, wrinkled by the uprise of long intermittent ridges, with broad plains and basins between them. Each of these forms an independent mountain-range. In the heart of Europe, the Bernese Oberland, the Pennine, Lepontine, Rhaetic, and other ranges form one great Alpine chain or system.

In a great mountain-chain, such as the Alps, Himalayas, or Andes, there is one general persistent trend for the successive ridges. Here and there, lateral offshoots may diverge, but the dominant direction of the axis of the main chain is generally observed by its component ridges until they disappear. Yet while the general parallelism is preserved, no single range may be traceable for more than a comparatively short distance; it may be found to pass insensibly into another, while a third may be seen to begin on a slightly different line, and to continue with the same dominant trend until it in turn becomes confluent. The various ranges are thus apt to assume an arrangement *en échelon*.

The ranges are separated by *longitudinal* valleys, that is, depressions coincident with the general direction of the chain. These, though sometimes of great length, are relatively of narrow width. The valley of the Rhône, from the source of the river down to Martigny, offers an excellent example. By a second series of valleys the ranges are trenched, often to a great depth, and in a direction transverse to the general trend. The Rhône furnishes also an example of one of these *transverse* valleys, in its course from Martigny to the Lake of Geneva. In most mountain regions, the heads of two adjacent transverse valleys are often connected by a depression or *pass* (*col*, *joch*).

A large block of mountain ground, rising into one or more dominant summits, and more or less distinctly defined by longitudinal and traverse valleys, is termed in French a *massif*—a word for which there is no good English equivalent. Thus in the Swiss Alps we have the massifs of the Glärnisch, the Tödi, the Matterhorn, the Jungfrau, etc.

Very exaggerated notions are common regarding the angle of declivity in mountains. Sections drawn across any mountain or mountain-chain on a true scale, that is, with the length and height on the same scale, bring out the fact that, even in the loftiest mountains, the breadth of base is always very much greater than the height. Actual vertical precipices are less frequent than is usually supposed, and even when they do occur, generally form minor incidents in the declivities of mountains. Slopes of more than 30° in angle are likewise far less abundant than casual tourists believe. Even such steep declivities as those of 38° or 40° are most frequently found as *talus*-slopes at the foot of crumbling cliffs, and represent the angle of repose of the disintegrated débris. Here and there, where the blocks loosened by weathering are of large size, they may accumulate upon each other in such a manner that for short distances the average angle of declivity may mount as high as 65°. But such steep slopes are of limited extent. Declivities exceeding 40°, and bearing a large proportion to the total dimensions of hill or mountain, are always found to consist of naked solid rock. In estimating angles of inclination from a distance, the student will learn by practice how apt is the eye to be deceived by perspective and to exaggerate the true declivity, sometimes to mistake a horizontal for a highly inclined or vertical line. The mountain outline shown in Fig. 2 presents a slope of 25° between *a* and *b*, of 45° between *b* and *c*, of 17° between *c* and *d*, of 40° between *d* and *e*, and of 70° between *e* and *f*. At a great distance, or with bad conditions of atmosphere, these might be believed to be the real declivities. Yet if the same angles be observed in another way (as on a cottage roof at B), we may learn that an apparently inclined surface may really be horizontal (as from *a* to *b* and from *c* to *d*), and that by the effect of perspective, slopes may be made to appear much steeper than they really are.[27]

Fig. 3.—Section from the Jura to Mont Blanc, on the same scale for length and height. *j*, Jura; *s*, Lake of Geneva; *v*, Voirons; *m*, Mole; *a*, Aiguille de Varens; *b*, Brevent; *mb*, Mont Blanc

Much evil has resulted in geological research from the use of exaggerated angles of slope in sections and diagrams. It is therefore desirable that the student should, from the beginning, accustom himself to the drawing of outlines as

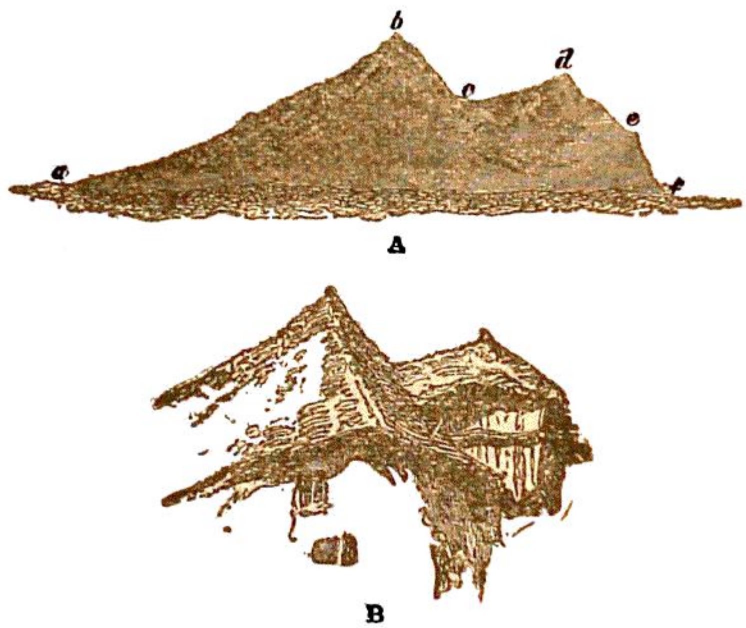

Fig. 2.—Angles of Slope where the eye may be deceived by perspective. (After Ruskin.) A, Mountain outline; B, The same outline as shown by cottage roof

nearly as possible on a true scale. The accompanying section of the Alps by De la Beche (Fig. 3) is of interest in this respect, as one of the earliest illustrations of the advantage of constructing geological sections on a true scale as to the relative proportions of height and length.[28]

[27] Mr. Ruskin has well illustrated this point. See "Modern Painters," vol. iv. p. 183, whence the illustrations in the text are taken.

[28] "Sections and Views, illustrative of Geological Phenomena," 1830. Geol. Observer, p. 646.

Table-lands or *Plateaus* are elevated regions of flat or undulating country, rising to heights of 1000 feet and upward above the level of the sea. They are sometimes bordered with steep slopes, which descend from their edges, as the table-land of the Spanish peninsula does into the sea. In other cases, they gradually sink into the plains and have no definite boundaries; thus the prairie-land west of the Missouri slowly and imperceptibly ascends until it becomes a vast plateau from 4000 to 5000 feet above the sea. Occasionally a high table-land is encircled with lofty mountains, as in those of Quito and Titicaca among the Andes, and that of the heart of Asia; or it forms in itself the platform on which lines of mountains stand, as in North America, where the ranges included within the Rocky Mountains reach elevations of from 10,000 to 14,000 feet above the sea, but not more than from 5000 to 10,000 feet above the table-land.

Two types of table-land structure may be observed. 1. Table-lands consisting of level or gently undulated sheets of rock, the general surface of the country corresponding with that of the stratification. The Rocky Mountain plateau is an example of this type, which may be called that of Deposit, for the flat strata have been equably upraised nearly in the position in which they were deposited. 2. Table-lands formed out of contorted, crystalline, or other rocks, which have been planed down by superficial agents. This type, where the external form is independent of geological structure, may be termed that of Erosion. The *fjelds* of Norway are portions of such a table-land. In proportion to its antiquity, a plateau is trenched by running water into systems of valleys, until in the end it may lose its plateau character and pass into the second type of mountain-ground above described. This change has largely altered the ancient table-land of Scandinavia, as will be illustrated in Book VII.

Plains are tracts of lowland (under 1000 feet in height) which skirt the sea-board of the continents and stretch inland up the river valleys. The largest plain in the world is that which, beginning in the centre of the British Islands, stretches across Europe and Asia. On the west, it is bounded by the ancient table-lands of Scandinavia, Scotland and Wales on the one hand, and those of Spain, France and Germany on the other. Most of its southern boundary is formed by the vast belt of high ground which spreads from Asia Minor to the east of Siberia. Its northern margin sinks beneath the waters of the Arctic Ocean. This vast region is divided into an eastern and western tract by the low chain of the Ural Mountains, south of which its general level sinks, until underneath the Caspian Sea it reaches a depression of about 3000 feet below sea-level. Along the eastern sea-board of America lies a broad belt of low plains, which attain their greatest dimensions in the regions watered by the larger rivers. Thus they cover thousands of square miles on the north side of the Gulf of Mexico, and extend for hundreds of miles up the valley of the Mississippi. Almost the whole of the valleys of the Orinoco, Amazon and La Plata is occupied with vast plains.

From the evidence of upraised marine shells, it is certain that large portions of the great plain of the Old World comparatively recently formed part of the sea-floor. It is likewise probable that the beds of some inclosed sea-basins, such as that of the North Sea, have formerly been plains of the dry land.

It is obvious, from their distribution along river-valleys, and on the areas between the base of high grounds and the sea, that plains are essentially areas of deposit. They are the tracts that have received the detritus washed down from the slopes above them, whether that detritus has originally accumulated on the land or below the sea. Their surface presents everywhere loose sandy, gravelly, or clayey formations, indicative of its comparatively recent subjection to the operation of running water.

(2.) Coast-lines.—A mere inspection of a map of the globe brings before the mind the striking differences which the masses of land present in their line of junction with the sea. As a rule, the southern continents possess a more uniform unindented coast-line than the northern. It has been estimated that the ratios between area and coast-line among the different continents, stand approximately as in the following table:

Northern	Europe	has 1 geographical mile	of coast-line to	143 sq. m.	of surface
	North America	"	"	265	"
	Asia including the islands		"	469	"
Southern	Africa	"	"	895	"
	South America	"	"	434	"
	Australia	"	"	332	"

In estimating the relative potency of the sea and of the atmospheric agents of disintegration, in the task of wearing down the land, it is evidently of great importance to take into account the amount of surface respectively exposed to their operations. Other things being equal, there is relatively more marine erosion in Europe than in North America. But we require also to consider the nature of the coast-line, whether flat and alluvial, or steep and rocky, or with some intermediate blending of these two characters. By attending to this point, we are soon led to observe such great differences in the character of coast-lines, and such an obvious relation to differences of geological structure, on the one hand, and to diversities in the removal or deposit of material, on the other, as to suggest that the present coast-lines of the globe cannot be aboriginal, but must be referred to the operation of geological agents still at work. This inference is amply sustained by more detailed investigation. While the general distribution of land and water must undoubtedly be assigned to terrestrial movements affecting the solid globe, the present actual coasts of the land have chiefly been produced by local causes. Headlands project from the land because, for the most part, they consist of rock which has been better able to withstand the shock of the breakers. Bays and creeks, on the other hand, have been cut by the waves out of less durable materials. Again, by the sinking of land, ranges of hills have become capes and headlands, while the valleys have passed into the condition of bays, inlets, or fjords. By the uprise of the sea-bottom, tracts of low alluvial ground have been added to the land. Hence, speculations as to the history of the elevation of the land, based merely upon inferences from the form of coast-lines as expressed upon ordinary maps, to be of real service, demand a careful scrutiny of the actual coast-lines, and an amount of geological investigation which would require long and patient toil for its accomplishment.

Passing from the mere external form of the land to the composition and structure of its materials, we may begin by considering the general density of the entire globe, computed from observations and compared with that of the outer and accessible portion of the planet. Reference has already been made to the comparative density of the earth among the other members of the solar system. In inquiries regarding the history of our globe, the density of the whole mass of the planet, as compared with water—the standard to which the specific gravities of terrestrial bodies are referred—is a question of prime importance. Various methods have been employed for determining the earth's density. The deflection of the plumb-line on either side of a mountain of known structure and density, the time of oscillation of the pendulum at great heights, at the sea-level, and in deep mines, and the comparative force of gravitation as measured by the torsion balance, have each been tried with the following various results:

Plumb-line experiments on Schichallien (Maskelyne and Playfair) gave as the mean density of the earth	4·713
Do. on Arthur's Seat, Edinburgh (James)	5·316
Pendulum experiments on Mont Cenis (Carlini and Giulio)	4·950
Do. in Harton coal-pit, Newcastle (Airy)	6·565
Torsion balance experiments (Cavendish, 1798)	5·480
Do. do. (Reich, 1838)	5·49
Do. do. (Baily, 1843)	5·660
Do. do. (Cornu and Baille, 1872–73)	5·50–5·56

Though these observations are somewhat discrepant, we may feel satisfied that the globe has a mean density neither much more nor much less than 5·5; that is to say, it is five and a half times heavier than one of the same dimensions formed of pure water. Now the average density of the materials which compose the accessible portions of the earth is between 2·5 and 3; so that the mean density of the whole globe is about twice as much as that of its outer part. We might, therefore, infer that the inside consists of much heavier materials than the outside, and consequently that the mass of the planet must contain at least two dissimilar portions—an exterior lighter crust or rind, and an interior heavier nucleus. But the effect of pressure must necessarily increase the specific gravity of the interior, as will be alluded to further on.

§ 2. **The Crust.**—It was formerly a prevalent belief that the exterior and interior of the globe differed from each other to such an extent that, while the outer parts were cool and solid, the vastly more enormous inner intensely hot part was more or less completely liquid. Hence the term "crust" was applied to the external rind in the usual sense of that word. This crust was variously computed to be ten, fifteen, twenty, or more miles in thickness. In the accompanying diagram (Fig. 4), for example, the thick line forming the circle represents a relative thickness of 100 miles. There are so many proofs of enormous and wide-spread corrugation of the materials of the earth's outer layers, and such abundant traces of former volcanic action, that geologists have naturally regarded the doctrine of a thin crust over a liquid interior as necessary for the explanation of a large class of terrestrial phenomena. For reasons which will be afterward given, however, this doctrine has been opposed by eminent physicists, and is now abandoned by most geologists. Nevertheless the term "crust" continues to be used, apart from all theory regarding the nucleus, as a convenient word to denote those cool, upper or outer layers of the earth's mass in the structure and history of which, as the only portions of the planet accessible to human observation, lie the chief materials of geological investigation. The chemical and mineral constitution of the crust is fully discussed in later pages (p. 112 *et seq.*).

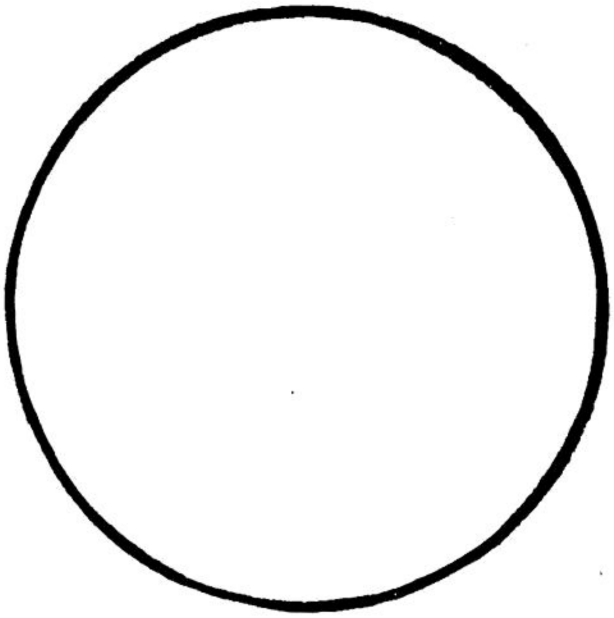

Fig. 4.—Supposed Crust of the Earth, 100 Miles thick

§ 3. **The Interior or Nucleus.**—Though the mere outside skin of our planet is all with which direct acquaintance can be expected, the irregular distribution of materials beneath the crust may be inferred from the present distribution of land and water, and the observed differences in the amount of deflection of the plumb-line near the sea and near mountain-chains. The fact that the southern hemisphere is almost wholly covered with water, appears only explicable, as already remarked, on the assumption of an excess of density in the mass of that half of the planet. The existence of such a vast sheet of water as that of the Pacific Ocean is to be accounted for, says Archdeacon Pratt, by the presence of "some excess of matter in the solid parts of the earth between the Pacific Ocean and the earth's centre, which retains the water in its place, otherwise the ocean would flow away to the other parts of the earth."[29] The same writer points out that a deflection of the plumb-line toward the sea, which has in a number of cases been observed, indicates that "the density of the crust beneath the mountains must be less than that below the plains, and still less than that below the ocean-bed.[30] Apart, therefore, from the depressions of the earth's surface, in which the oceans lie, we must regard the internal density, whether of crust or nucleus, to be somewhat irregularly arranged—there being an excess of heavy materials in the water-hemisphere, and beneath the ocean-beds as compared with the continental masses.

It has been argued from the difference between the specific gravity of the whole globe and that of the crust,

[29] "Figure of the Earth," 4th edit. p. 236.

[30] Op. cit. p. 200. See also Herschel, "Phys. Geog." § 13; O. Fisher, Cambridge Phil. Trans. xii. part ii.; "Physics of the Earth's Crust," p. 75. Phil. Mag. July, 1886. Faye, Comptes rendus, cii. (1886), p. 651.

that the interior must consist of heavier material, and may be metallic. But the effect of the enormous internal pressure, it might be supposed, should make the density of the nucleus much higher, even if the interior consisted of matter which, on the surface, would be no heavier than that of the crust. In fact, we might, on the contrary, argue for the probable comparative lightness of the substance composing the nucleus. That the total density of the planet does not greatly exceed its observed amount, may indicate that some antagonistic force counteracts the effect of pressure. The only force we can suppose capable of so acting is heat, though to what extent this counterbalancing takes place is still unknown. It must be admitted that we are still in ignorance of the law that regulates the compression of solids under such vast pressure as must exist within the earth's interior. We know that gases and vapors may be compressed into liquids, sometimes even into solids, and that in the liquid condition another law of compressibility begins. We know also from experiment that some substances have their melting-point raised by pressure.[31] It may be that the same effect takes place within the earth; that pressure increasing inward to the centre of the globe, while augmenting the density of each successive shell, may retain the whole in a solid condition, yet at temperatures far above the normal melting-points at the surface. Hence, on this view of the matter, it is conceivable that the difference between the density of the whole globe and that of the crust may be due to pressure, rather than to any essential difference of composition. Laplace proposed the hypothesis that the increase of the square of

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[31] Under a pressure of 792 atmospheres, spermaceti has its melting-point raised from 51° to 80·2°, and wax from 64·5° to 80·2°.

the density is proportional to the increase of the pressure, which gives a density of 8·23 at half the terrestrial radius and of 10·74 at the centre. From another law proposed by Prof. Darwin, the density at half the radius is only 7·4, but thence toward the centre increases rapidly up to infinity.[32] Dr. Pfaff believes that the mean terrestrial density of 5·5 is not incompatible with the notion that the whole globe consists of materials of the same density as the rocks of the crust.[33] It is possible that the gases dissolved in the hot magma of the nucleus, with their very high tension, may counteract the effects of compression and thus reduce density.

Analogies in the solar system, however, as well as the actual structure of the rocky crust of the globe, suggest that heavier metallic ingredients possibly predominate in the nucleus. If the materials of the globe were once, as they are believed to have been, in a liquid condition, they would then doubtless be subject to internal arrangement, in accordance with their relative specific gravities. We may conceive that, as in the case of the sun, as well as of the solar system generally (*ante*, p. 25), there would be, so long as internal mobility lasted, a tendency in the denser elements of our planet to gravitate toward the centre, in the lighter to accumulate outside. That a distribution of this nature has certainly taken place to some extent, is evident from the structure of the envelopes and crust. It is what might be expected, if the constitution of the globe resembles, on a small scale, the larger planetary system of which

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[32] See Fisher "Physics of Earth's Crust," 2d edit. chap. ii. Legendre supposed that the density being 2·5 at the surface, it is 8·5 at half the length of the radius and 11·3 at the centre. More recently E. Roche calculated these densities to be 2·1, 8·5 and 10·6 respectively.

[33] "Allgemeine Geologie als exacte Wissenschaft," p. 42.

it forms a part. The existence even of a metallic interior has been inferred from the metalliferous veins which traverse the crust, and which are commonly supposed to have been filled from below.

Evidence of Internal Heat.—In the evidence obtainable as to the former history of the earth, no fact is of more importance than the existence of a high temperature beneath the crust, which has now been placed beyond all doubt. This feature of the planet's organization is made clear by the following proofs:

(1.) *Volcanoes.*—In many regions of the earth's surface, openings exist from which steam and hot vapors, ashes and streams of molten rock, are from time to time emitted. The abundance and wide diffusion of these openings, inexplicable by any mere local causes, must be regarded as indicative of a very high internal temperature. If to the still active vents of eruption, we add those which have formerly been the channels of communication between the interior and the surface, there are perhaps few large regions of the globe where proofs of volcanic action cannot be found. Everywhere we meet with masses of molten rock which have risen from below, as if from some general reservoir. The phenomena of active volcanoes are fully discussed in Book III. Part I.

(2.) *Hot Springs.*—Where volcanic eruptions have ceased, evidence of a high internal temperature is still often to be found in springs of hot water which continue for centuries to maintain their heat. Thermal springs, however, are not confined to volcanic districts. They sometimes rise even in regions many hundreds of miles distant from any active volcanic vent. The hot springs of Bath (temp. 120° Fahr.) and Buxton (temp. 82° Fahr.) in England are fully 900 miles from the Icelandic volcanoes on the one side, and 1100 miles from those of Italy and Sicily on the other.

(3.) *Borings, Wells and Mines.*—The influence of the seasonal changes of temperature extends downward from the surface to a depth which varies with latitude, with the thermal conductivity of soils and rocks, and perhaps with other causes. The cold of winter and the heat of summer may be regarded as following each other in successive waves downward, until they disappear along a limit at which the temperature remains constant. This zone of invariable temperature is commonly believed to lie at a depth of somewhere between 60 and 80 feet in temperate regions. At Yakutsk in Eastern Siberia (lat. 62° N.), however, as shown in a well-sinking, the soil is permanently frozen to a depth of about 700 feet.[34] In Java, on the other hand, a constant temperature is said to be met with at a depth of only 2 or 3 feet.[35]

It is a remarkable fact, now verified by observation all over the world, that below the limit of the influence of ordinary seasonal changes the temperature, so far as we yet know, is nowhere found to diminish downward. It always rises; and its rate of increment never falls much below the average. The only exceptional cases occur under circumstances not difficult of explanation. On the one hand, the neighborhood of hot-springs, of large masses of lava, or of other manifestations of volcanic activity, may raise the subterranean temperature much above its normal condition; and this augmentation may not disappear for many thousand years after the volcanic activity has wholly ceased, since the cooling down of a subterranean mass of

[34] Helmersen, Brit. Assoc. Rep. 1871, p. 22. See vol. for 1886, p. 271.
[35] Junghuhn's "Java," ii. p. 771.

lava must necessarily be a very slow process. Lord Kelvin has even proposed to estimate the age of subterranean masses of intrusive lava from their excess of temperature above the normal amount for their isogeotherms (lines of equal earth-temperature), some probable initial temperature and rate of cooling being assumed. On the other hand, the spread of a thick mass of snow and ice over any considerable area of the earth's surface, and its continuance there for several thousand years, would so depress the isogeotherms that, for many centuries afterward, there would be a fall of temperature for a certain distance downward. At the present day, in at least the more northerly parts of the northern hemisphere, there are such evidences of a former more rigorous climate, as in the well-sinking at Yakutsk just referred to.[36] Lord Kelvin (Sir W. Thomson)[37] has calculated that any considerable area of the earth's surface covered for several thousand years by snow or ice, and retaining, after the disappearance of that frozen covering, an average surface temperature of 13° C., "would during 900 years show a decreasing temperature for some depth down from the surface, and 3600 years after the clearing away of the ice would still show residual effect of the ancient cold, in a half rate of augmentation of temperature downward in the upper strata, gradually increasing to the whole normal rate, which would be sensibly reached at a depth of 600 metres."

Beneath the limit to which the influence of the changes of the seasons extends, observations all over the globe, and

[36] Professor Prestwich (Inaugural Lecture, 1875, p. 45) has suggested that to the more rapid refrigeration of the earth's surface during this cold period, and to the consequent depression of the subterranean isothermal lines, the alleged present comparative quietude of the volcanic forces is to be attributed, the internal heat not having yet recovered its dominion in the outer crust.

[37] Brit. Assoc. Reports, 1876, Sections, p. 3.

at many different elevations, give a rate of increase of temperature downward, or "temperature gradient," which has been usually taken to be 1° Fahr. for every 50 or 60 feet of descent, this computation being based especially on observations in deep mines and borings. Professor Prestwich concluded from a large series of observations collated by him, that the average increment might be taken at 1° Fahr. for every 45 feet.[38] Observations taken in the extraordinarily deep boring at Schladebach, near Dürrenberg, showed that in a depth of 5736 feet the average rise of temperature was 1° Fahr. for every 65 feet.[39] According to data collected by a Committee of the British Association, the average gradient appears to be 1° Fahr. for every 64 feet, or $\frac{1}{64}$ of a degree per foot.

Isogeotherms near the surface follow approximately the contours of the surface, but are flatter than these, and "their flattening increases as we pass to lower ones, until at a considerable depth they become sensibly horizontal planes. The temperature gradient is consequently steepest beneath gorges and least steep beneath ridges."[40]

Irregularities in the Downward Increment of Heat.—While there is everywhere a progressive increase of temperature downward, its rate is by no means uniform. The more detailed observations which

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[38] Proc. Roy. Soc. xli. (1885), p. 55.

[39] Brit. Assoc. 1889. Report of Underground Temperature Committee.

[40] J. D. Everett, Brit. Assoc. 1879, Sections, p. 345. Compare also the elaborate observations made in the St. Gothard Tunnel, F. Stapff, "Rapports, Conseil Féd. St. Gothard," vol. viii., and "Geologische Durchschnitte des Gothard Tunnels"; "Étude de l'Influence de la Chaleur de l'Intérieur de la Terre," etc., Revue. Univ. Mines, 1879–80. Min. Proc. N. England Inst. Mining-Mechan. Engin. xxxii. (1883), p. 19. "Reports of Committee on Underground Temperature," Brit. Assoc. Rep. from 1868 onward, with summary of results in the volume for 1882. A voluminous and valuable collection of data bearing on this subject was compiled by Prof. Prestwich and is published in Proc. Roy. Soc. xli. (1885), p. 1.

have been made in recent years have brought to light the important fact that considerable variations in the rate of increase take place, even in the same bore. The temperatures obtained at different depths in the Rose Bridge colliery shaft, Wigan, for instance, read as in the following columns:

Depth in Yards	Temperature (Fahr.)	Depth in Yards	Temperature (Fahr.)
558	78	745	89
605	80	761	90½
630	83	775	91½
663	85	783	92
671	86	800	93
679	87	806	93½
734	88½	815	94

At La Chapelle, in an important well made for the water-supply of Paris, observations have been taken of the temperature at different depths, as shown in the subjoined table:[41]

Depth in Metres	Temperature (Fahr.)	Depth in Metres	Temperature (Fahr.)
100	59·5	500	72·6
200	61·8	600	75·0
300	65·5	660	76·0
400	69·0		

In drawing attention to the foregoing temperature-observations at the Rose Bridge colliery—the deepest mine in Great Britain—Prof. Everett points out that, assuming the surface temperature to be 49° Fahr., in the first 558 yards, the rate of rise of temperature is 1° for 57·7 feet; in the next 257 yards it is 1° in 48·2 feet; in the portion between 605 and 671 yards—a distance of only 198 feet—it is 1° in 33 feet; in the lowest portion of 432 feet it is 1° in 54 feet.[42] When such irregularities occur in the same vertical shaft, it is not surprising that the average should vary so much in different places.

[41] Brit. Assoc. Rep. 1873, Sections, p. 254.
[42] Brit. Assoc. Rep. 1870, Sections, p. 31.

There can be little doubt that one main cause of these variations is to be sought in the different thermal conductivities of the rocks of the earth's crust. The first accurate measurements of the conducting powers of rocks were made by the late J. D. Forbes at Edinburgh (1837–1845). He selected three sites for his thermometers, one in "trap-rock" (a porphyrite of Lower Carboniferous age), one in loose sand, and one in sandstone, each set of instruments being sunk to depths of 3, 6, 12 and 24 French feet from the surface. He found that the wave of summer heat reached the bulb of the deepest instrument (24 feet) on 4th January in the trap-rock, on 25th December in the sand, and on 3d November in the sandstone, the trap-rock being the worst conductor and the solid sandstone by far the best.[43]

As a rule, the lighter and more porous rocks offer the greatest resistance to the passage of heat, while the more dense and crystalline offer the least resistance. The resistance of opaque white quartz is expressed by the number 114, that of basalt stands at 273, while that of cannel coal stands very much higher at 1538, or more than thirteen times that of quartz.[44]

It is evident also, from the texture and structure of most rocks, that the conductivity must vary in different directions through the same mass, heat being more easily conducted along than across the "grain," the bedding, and the other numerous divisional surfaces. Experiments have been made to determine these variations in a number of rocks. Thus the conductivity in a direction transverse to the divi-

[43] Trans. Roy. Soc. Edin. xvi. p. 211.

[44] Herschel and Lebour (British Association Committee on Thermal Conductivities of Rocks), Brit. Assoc. Rep. 1875, p. 59. The final Report is in the vol. for 1881.

sional planes being taken as unity, the conductivity parallel with these planes was found in a variety of magnesian schist to be 4·028. In certain slates and schistose rocks from central France, the ratio varied from 1 : 2·56 to 1 : 3·952. Hence in such fissile rocks as slate and mica-schist, heat may travel four times more easily along the planes of cleavage or foliation than across them.[45]

In reasoning upon the discrepancies in the rate of increase of subterranean temperatures, we must also bear in mind that convection by percolating streams of water must materially affect the transference of heat from below.[46] Certain kinds of rock are more liable than others to be charged with water, and, in almost every boring or shaft, one or more horizons of such water-bearing rocks are met with. The effect of interstitial water is to diminish thermal resistance. Dry red brick has its resistance lowered from 680 to 405 by being thoroughly soaked in water, its conductivity being thus increased 68 per cent. A piece of sandstone has its conductivity heightened to the extent of 8 per cent by being wetted.[47]

Mallet contended that the variations in the amount of increase in subterranean temperature are too great to permit us to believe them to be due merely to differences in the transmission of the general internal heat, and that they point to local accessions of heat arising from transformation of the mechanical work of compression, which is due

[45] Report of Committee on Thermal Conductivities of Rocks, Brit. Assoc. Rep. 1875, p. 61. Jannettaz, Bull. Soc. Géol. France (April–June, 1874), ii. p. 264. This observer has carried out a series of detailed researches on the propagation of heat through rocks which will be found in Bull. Soc. Géol. France, tomes i.-ix. (3d series).

[46] In the great bore of Sperenberg (4172 feet, entirely in rock-salt, except the first 283 feet) there is evidence that the water near the top is warmed 4½° Fahr. by convection. Brit. Assoc. 1882, p. 78.

[47] Herschel and Lebour, Brit. Assoc. Rep. 1875, p. 58.

to the constant cooling and contraction of the globe.[48] But it may be replied that these variations are not greater than, from the known divergences in the conductivities of rocks, they might fairly be expected to be.

Probable Condition of the Earth's Interior.—Various theories have been propounded on this subject. There are only three which merit serious consideration. (1.) One of these supposes the planet to consist of a solid crust and a molten interior. (2.) The second holds that, with the exception of local vesicular spaces, the globe is solid and rigid to the centre. (3.) The third contends that while the mass of the globe is solid, there lies a liquid substratum beneath the crust.

1. *The arguments in favor of internal liquidity* may be summed up as follows. (*a.*) The ascertained rise of temperature inward from the surface is such that, at a very moderate depth, the ordinary melting-point of even the most refractory substances would be reached. At 20 miles the temperature, if it increases progressively, as it does in the depths accessible to observation, must be about 1760° Fahr.; at 50 miles it must be 4600°, or far higher than the fusing-point even of so stubborn a metal as platinum, which melts at 3080° Fahr.[49] (*b.*) All over the world volcanoes exist from which steam and torrents of molten lava are from time to time erupted. Abundant as are the active volcanic vents, they form but a small proportion of the whole which have been in operation since early geological time. It has been inferred, therefore, that these numerous funnels of commu-

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48 "Volcanic Energy," Phil. Trans. 1875.

49 But Lord Kelvin (Sir W. Thomson) has shown that if the rate of increase of temperature is taken to be 1° for every 51 feet for the first 100,000 feet, it will begin to diminish below that limit, being only 1° in 2550 feet at 800,000 feet, and then rapidly lessening. Trans. Roy. Soc. Edin. xxiii. p. 163.

nication with the heated interior could not have existed and poured forth such a vast amount of molten rock, unless they drew their supplies from an immense internal molten nucleus. (*c.*) When the products of volcanic action from different and widely-separated regions are compared and analyzed, they are found to exhibit a remarkable uniformity of character. Lavas from Vesuvius, from Hecla, from the Andes, from Japan, and from New Zealand present such an agreement in essential particulars as, it is contended, can only be accounted for on the supposition that they have all emanated from one vast common source.[50] (*d.*) The abundant earthquake-shocks which affect large areas of the globe are maintained to be inexplicable unless on the supposition of the existence of a thin and somewhat flexible crust. These arguments, it will be observed, are only of the nature of inferences drawn from observations of the present constitution of the globe. They are based on geological data, and have been frequently urged by geologists as supporting the only view of the nature of the earth's interior, supposed by them to be compatible with geological evidence.

2. *The arguments in favor of the internal solidity of the earth* are based on physical and astronomical considerations of the greatest importance. They may be arranged as follows:

(*a.*) Argument from precession and nutation.—The problem of the internal condition of the globe was attacked as far back as the year 1839 by Hopkins, who calculated how far the planetary motions of precession and nutation would be influenced by the solidity or liquidity of the earth's inte-

[50] See D. Forbes, Popular Science Review, April, 1869.

rior. He found that the precessional and nutational movements could not possibly be as they are, if the planet consisted of a central core of molten rock surrounded with a crust of twenty or thirty miles in thickness; that the least possible thickness of crust consistent with the existing movements was from 800 to 1000 miles; and that the whole might even be solid to the centre, with the exception of comparatively small vesicular spaces filled with melted rock.[61]

M. Delaunay[62] threw doubt on Hopkins' views, and suggested that, if the interior were a mass of sufficient viscosity, it might behave as if it were a solid, and thus the phenomena of precession and nutation might not be affected. Lord Kelvin (Sir W. Thomson), who had already arrived at the conclusion that the interior of the globe must be solid, and acquiesced generally in Hopkins' conclusions, remarked that the hypothesis of a viscous and quasi-rigid interior "breaks down when tested by a simple calculation of the amount of tangential force required to give to any globular portion of the interior mass the precessional and nutational motions which, with other physical astronomers, M. Delaunay attributes to the earth as a whole.[53] He held the earth's crust down to depths of hundreds of kilometres to be capable of resisting such a tangential stress (amounting to nearly $\frac{1}{10}$th of a gramme weight per square centimetre) as would with great rapidity draw out of shape any plastic substance which could properly be termed a viscous fluid, and

[61] Phil. Trans. 1839, p. 381; 1840, p. 193; 1842, p. 43; Brit. Assoc. 1847.

[62] In a paper on the hypothesis of the interior fluidity of the globe, Comptes rendus, July 13, 1868. Geol. Mag. v. p. 507. See also H. Hennessy, Comptes rendus, March 6, 1871, Geol. Mag. viii. p. 216. Nature, xv. p. 78. O. Fisher, "Physics of the Earth's Crust," 2d Edition, 1889.

[53] Nature, February 1, 1872.

he concluded "that the rigidity of the earth's interior substance could not be less than a millionth of the rigidity of glass without very sensibly augmenting the lunar nineteen-yearly nutation.[54]

In Hopkins' hypothesis he assumed the crust to be infinitely rigid and unyielding, which is not true of any material substance. Lord Kelvin subsequently returning to the problem, in the light of his own researches in vortex-motion, found that, while the argument against a thin crust and vast liquid interior is still invincible, the phenomena of precession and nutation do not decisively settle the question of internal fluidity, as Hopkins, and others following him, had believed, though the solar semi-annual and lunar fortnightly nutations absolutely disprove the existence of a thin rigid shell full of liquid. If the inner surface of the crust or shell were rigorously spherical, the interior mass of supposed liquid could experience no precessional or nutational influence, except in so far as, if heterogeneous in composition, it might suffer from external attraction due to non-sphericity of its surfaces of equal density. But "a very slight deviation of the inner surface of the shell from perfect sphericity would suffice, in virtue of the quasi-rigidity due to vortex-motion, to hold back the shell from taking sensibly more precession than it would give to the liquid, and to cause the liquid (homogeneous or heterogeneous) and the shell to have sensibly the same precessional motion as if the whole constituted one rigid body."[55] The problem presented by the precession of a viscous spheroid has more recently been discussed by Prof. George Darwin, who arrives at results nearly the same as those announced by Lord Kel-

[54] Loc. cit. p. 258.
[55] Lord Kelvin (Sir W. Thomson), Brit. Assoc. Rep. 1876, Sections, p. 5.

vin regarding the slight difference between the precession of a fluid and a rigid spheroid.[56]

The assumption of a comparatively thin crust requires that the crust shall have such perfect rigidity as is possessed by no known substance. The tide-producing force of the moon and sun exerts such a strain upon the substance of the globe, that it seems in the highest degree improbable that the planet could maintain its shape as it does unless the supposed crust were at least 2000 or 2500 miles in thickness.[57] That the solid mass of the earth must yield to this strain is certain, though the amount of deformation is so slight as to have hitherto escaped all attempts to detect it.[58] Had the rigidity been even that of glass or of steel, the deformation would probably have been by this time detected, and the actual phenomena of precession and nutation, as well as of the tides, would then have been very sensibly diminished.[59] The conclusion is thus reached that the mass of the earth "is on the whole more rigid certainly than a continuous solid globe of glass of the same diameter."[60]

(*b*.) Argument from the tides.—The phenomena of the oceanic tides show that the earth acts as a rigid body either solid to the centre, or possessing so thick a crust (2500 miles or more) as to give to the planet practical solidity. Lord Kelvin remarks that "were the crust of continuous steel and 500 kilometres thick, it would yield very nearly as much as if it were India-rubber to the deforming influences of centrifugal force, and of the sun's and moon's attractions." It would yield, indeed, so freely to these attractions "that it

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[56] Phil. Trans. 1879, Part 2, p. 464.
[57] Lord Kelvin, Proc. Roy. Soc. April, 1862.
[58] See Association Française pour l'Avancement des Sciences, v. p. 281.
[59] Lord Kelvin, loc. cit.
[60] Ibid. Trans. Roy. Soc. Edin. xxiii. p. 157.

would simply carry the waters of the ocean up and down with it, and there would be no sensible tidal rise and fall of water relatively to land.[61] Prof. G. H. Darwin, in the series of papers already referred to, has investigated mathematically the bodily tides of viscous and semi-elastic spheroids, and the character of the ocean tides on a yielding nucleus.[62] His results tend to increase the force of Sir William Thomson's argument, since they show that "no very considerable portion of the interior of the earth can even distantly approach the fluid condition," the effective rigidity of the whole globe being very great.

(*c.*) Argument from relative densities of melted and solid rock.—The two preceding arguments must be considered decisive against the hypothesis of a thin shell or crust covering a nucleus of molten matter. It has been further urged, as an objection to this hypothesis, that cold solid rock is more dense than hot melted rock, and that even if a thin crust were formed over the central molten globe it would immediately break up and the fragments would sink toward the centre.[63] Recent experiments show that diabase (of density 3·017) contracts nearly 4 per cent on solidification, and that the resulting homogeneous glass has a density of only 2·717.[64] As has been already pointed out, the specific gravity of the interior is at least twice as much as that of the visible parts of the crust. If this difference be due, not merely to the effect of pressure, but to the presence in the interior of intensely heated metallic substances, we cannot

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[61] Lord Kelvin, Brit. Assoc. Rep. 1876, Sections, p. 7.

[62] Phil. Trans. 1879, Part 2. See also Brit. Assoc. Rep. 1882, Sects. p. 473.

[63] This objection has been repeatedly urged by Lord Kelvin. See Trans. Roy. Soc. Edin. xxiii. p. 157; and Brit. Assoc. Rep. 1870, Sections, p. 7.

[64] C. Barus, Phil. Mag. 1893, p. 174. It is nevertheless true that, from a cause merely mechanical, pieces of the original cold rock, though so much denser, will float for a time on the melted material. Ib. p. 189.

suppose that solidified portions of such rocks as granite and the various lavas could ever have sunk into the centre of the earth, so as to build up there the honey-combed cavernous mass which might have served as a nucleus in the ultimate solidification of the whole planet. If the earliest formed portions of the comparatively light crust were denser than the underlying liquid, they would no doubt descend until they reached a stratum with specific gravity agreeing with their own, or until they were again melted.[65]

3. *Hypothesis of a liquid substratum between a solid nucleus and the crust.*—Since the early and natural belief in the liquidity of the earth's interior has been so weightily opposed by physical arguments, geologists have endeavored to modify it in such a way as, if possible, to satisfy the requirements of physics, while at the same time providing an adequate explanation of the corrugation of the earth's crust, the phenomena of volcanoes, etc.[66] The hypothesis has been proposed of "a rigid nucleus nearly approaching the size of the whole globe, covered by a fluid substratum of no great thickness, compared with the radius, upon which a crust of lesser density floats in a state of equilibrium." The nucleus is assumed to owe its solidity to "the enormous pressure of the superincumbent matter, while the crust owes its solidity to having become cool. The fluid substratum is

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[65] See D. Forbes, Geol. Mag. vol. iv. p. 435. The evidence for the internal solidity of the earth is criticised by Dr. M. E. Wadsworth in the American Naturalist, 1884.

[66] See Dana in Silliman's Journal, iii. (1847), p. 147. Amer. Journ. Science (1873). The hypothesis of a fluid substratum has been advocated by Shaler. Proc. Bost. Nat. Hist. Soc. xi. (1868), p. 8. Geol. Mag. v. p. 511. J. Le Conte, Amer. Journ. Sci. 1872, 1873. O. Fisher, Geol. Mag. v. (new series), pp. 291 and 551. "Physics of the Earth's Crust," 1883. [This author in his second edition modifies this view.] Hill, Geol. Mag. v. (new series), pp. 262, 479. The idea of a viscous layer between the solidifying central mass and the crust was present in Hopkins' mind. Brit. Assoc. 1848, Reports, p. 48.

not under sufficient pressure to be rendered solid, and is sufficiently hot to be fluid, being probably more viscous in its lower portion through pressure and likewise passing into a viscous state in its upper parts through cooling, until it joins the crust."[67] The contraction and consolidation of this substratum are assumed as the explanation of the plication which the crust has certainly undergone.

It must be admitted that the widespread proofs of great crumpling of the rocks of the crust present a difficulty, for they indicate a capability of yielding to strain such as has been supposed impossible in a globe possessing on the whole the rigidity of steel or glass. But this difficulty may be more formidable in appearance than in reality. The earth must certainly possess such a degree of rigidity as to resist tidal deformation. Prof. Darwin has calculated the limiting rigidity in the materials of the earth which is necessary to prevent the weight of mountains and continents from reducing them to the fluid condition or else cracking, and has found that these materials must be as strong as granite 1000 miles below the surface, or else much stronger than granite near the surface.[68] But high rigidity, that is, elasticity of form, is not contradictory of plasticity. Even bodies like steel may, under suitable stress, be made to flow like butter (see *postea*, Book III. Part I. Sect. iv. § 3). While, therefore, the earth may possess as a whole the rigidity of steel, there seems no reason why, under sufficient strain, the outer portions may not be plicated or even reduced to the fluid condition. It is important "to distinguish viscosity, in which flow is caused by infinitesimal forces, from plasticity, in which permanent distor-

[67] Fisher, "Physics of Earth's Crust," 1st edit. p. 269.
[68] Proc. Roy. Soc. 1881, p. 432.

tion or flow only sets in when the stresses exceed a certain limit."[69]

In speculating on the plication of the earth's crust, we ought not to forget that, from the earliest times, the existing continental regions seem to have specially suffered from the efforts of the planet to adjust its external form to its diminishing diameter and lessening rapidity of rotation. They have served as lines of relief from the strain of compression during many successive epochs. It is along their axial lines—their long dominant mountain-ranges, that we should naturally look for evidence of corrugation. Away from these lines of weakness the ground has been upraised for thousands of square miles without plication of the rocks, as in the instructive region of the Western Territories of North America. Nor is there any proof that corrugation takes place beneath the great oceanic areas of subsidence.

It appears highly probable that the substance of the earth's interior is at the melting-point proper for the pressure at each depth. Any relief from pressure, therefore, may allow of the liquefaction of the matter so relieved. Such relief is doubtless afforded by the corrugation of mountain-chains and other terrestrial ridges. And it is in these lines of uprise that volcanoes and other manifestations of subterranean heat actually show themselves.

§ 4. **Age of the Earth and Measures of Geological Time.** —The age of our planet is a problem which may be attacked either from the geological or physical side.

1. The geological arguments rest chiefly upon the observed rates at which geological changes are being effected at the present time, and is open to the obvious preliminary objection that it assumes the existing rate of

[69] Prof. Darwin in a letter to the author, 9th January, 1884.

change as the measure of past revolutions—an assumption, however, which may be erroneous, for the present may be a period when all geological events march forward more slowly than they used to do. The argument proceeds on data partly of a physical and partly of an organic kind. (*a*.) The physical evidence is derived from such facts as the observed rates at which the surface of a country is lowered by rain and streams, and new sedimentary deposits are formed. These facts will be more particularly dwelt upon in later sections of this work. If we assume that the land has been worn away, and that stratified deposits have been laid down, nearly at the same rate as at present, then we must admit that the stratified portion of the crust of the earth must represent a very vast period of time.[70] (*b*.) On the other hand, human experience, so far as it goes, warrants the belief that changes in the organic world proceed with extreme slowness. Yet in the stratified rocks of the terrestrial crust we have abundant proof that the whole fauna and flora of the earth's surface have passed through numerous cycles of revolution—species, genera, families, orders, appearing and disappearing many times in succession. On any supposition, it must be admitted that these vicissitudes in the organic world can only have

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[70] Dr. Croll put this period at not less, but possibly much more, than 60 million years. Dr. Haughton gives a much more extended period. Estimating the present rate of deposit of strata at 1 foot in 8616 years, assuming the former rate to have been ten times more rapid, or 1 foot in 861·6 years, and taking the thickness of the stratified rocks of the earth's crust at 177,200 feet, he obtains a minimum of 200,000,000 years for the whole duration of geological time: "Six Lectures on Physical Geography," 1880, p. 94. Dr. Haughton has also proposed another geological measure of past time, based upon the assumed effects of continental upheaval (Proc. Roy. Soc. xxvi. (1877), p. 534). But Prof. Darwin has shown it to be inadmissible. (Op. cit. xxvii. (1878), p. 179.) For various opinions regarding geological measures of time see J. Phillips, Brit. Assoc. 1864: Croll, Phil. Mag. 1868: T. McK. Hughes, Proc. Roy. Inst. Great Britain, March 24, 1876: Dupont, Bull. Acad. Roy. Belgique, viii. (1884): T. Mellard Reade, Quart. Journ. Geol. Soc. 1888, p. 291.

been effected with the lapse of vast periods of time, though no reliable standard seems to be available whereby these periods are to be measured. The argument from geological evidence indicates an interval of probably not much less than 100 million years since the earliest forms of life appeared upon the earth, and the oldest stratified rocks began to be laid down.

2. The physical argument as to the age of our planet is based by Lord Kelvin upon three kinds of evidence: (1) the internal heat and rate of cooling of the earth; (2) the tidal retardation of the earth rotation; and (3) the origin and age of the sun's heat.

(1.) Applying Fourier's theory of thermal conductivity, he pointed out as far back as the year 1862, that in the known rate of increase of temperature downward beneath the surface, and the rate of loss of heat from the earth, we have a limit to the antiquity of the planet. He showed, from the data available at the time, that the superficial consolidation of the globe could not have occurred less than 20 million years ago, or the underground heat would have been greater than it is; nor more than 400 million years ago, otherwise the underground temperature would have shown no sensible increase downward. He admitted that very wide limits were necessary. In subsequently discussing the subject, he inclined rather toward the lower than the higher antiquity, but concluded that the limit, from a consideration of all the evidence, must be placed within some such period of past time as 100 millions of years. He would now restrict the time to about 20 millions.[71]

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[71] Trans. Roy. Soc. Edin. xxiii. p. 157. Trans. Geol. Soc. Glasgow, iii. p. 25. "Popular Lectures and Addresses," 2d edit. (1891), p. 397. Prof. Tait reduces the period to 10 or 15 millions. "Recent Advances in Physical Science," p. 167.

(2.) The reasoning from tidal retardation proceeds on the admitted fact that, owing to the friction of the tide-wave, the rotation of the earth is retarded, and is therefore slower now than it must have been at one time. Lord Kelvin contends that had the globe become solid some 10,000 million years ago, or indeed any high antiquity beyond 100 million years, the centrifugal force due to the more rapid rotation must have given the planet a very much greater polar flattening than it actually possesses. He admits, however, that though 100 million years ago that force must have been about 3 per cent greater than now, yet "nothing we know regarding the figure of the earth and the disposition of land and water would justify us in saying that a body consolidated when there was more centrifugal force by 3 per cent than now, might not now be in all respects like the earth, so far as we know it at present."[72]

(3.) The third kind of evidence leads to results similar to those derived from the two previous lines of reasoning. It is based upon calculations as to the amount of heat that would be available by the falling together of masses from space, which gave rise by their impact to our sun, and the rate at which this heat has been radiated. Assuming that the sun has been cooling at a uniform rate, Prof. Tait concludes that it cannot have supplied the earth, even at the present rate, for more than about 15 or 20 million years.[73] Lord Kelvin also believes that the sun's light will not last more than 5 or 6 millions of years longer.[74]

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[72] Trans. Geol. Soc. Glasgow, iii. p. 16. Prof. Tait, in repeating this argument, concludes that, taken in connection with the previous one, "it probably reduces the possible period which can be allowed to geologists to something less than 10 millions of years." "Recent Advances," p. 174. Compare Newcombe, "Popular Astronomy," p. 505.

[73] Op. cit. p. 174.

[74] "Popular Lectures," etc. p. 397.

There can be no doubt that the demands of the earlier geologists for an unlimited duration of past time, for the accomplishment of geological history, were extravagant and unnecessary. But it may be questioned how far the recent limitation of time proposed from physical considerations are really founded on well-established facts. The argument from the geological record in favor of a much longer period than physicists are disposed to concede is so strong that one is inclined to believe that these writers have overstated their case. The evidence from the nature of the sedimentary rocks, and from the succession of organic remains in these rocks, appears to me to demand an amount of time not far short of the hundred millions of years originally granted by Lord Kelvin.[75]

PART II.—AN ACCOUNT OF THE COMPOSITION OF THE EARTH'S CRUST—MINERALS AND ROCKS

The earth's crust is composed of mineral matter in various aggregates included under the general term Rock. A rock may be defined as a mass of matter composed of one or more simple minerals, having usually a variable chemical composition, with no necessarily symmetrical external form, and ranging in cohesion from mere loose debris up to the most compact stone. Granite, lava, sandstone, limestone, gravel, sand, mud, soil, marl and peat, are all recognized in a geological sense as rocks. The study of rocks is known as Lithology, Petrography or Petrology.

It will be most convenient to treat—1st, of the general chemical constitution of the crust; 2d, of the minerals of

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[75] I have touched on this question in my Presidential Address to the British Association 1892. But see a paper by Mr. Clarence King, Amer. Journ. Sci. xlv. (1893).

which rocks mainly consist; 3d, of the methods employed for the determination of rocks; 4th, of the external characters of rocks; 5th, of the internal texture and structure of rocks; 6th, of the classification of rocks; and 7th, of the more important rocks occurring as constituents of the earth's crust.

§ i. General Chemical Constitution of the Crust

Direct acquaintance with the chemical constitution of the globe must obviously be limited to that of the crust, though by inference we may eventually reach highly probable conclusions regarding the constitution of the interior. Chemical research has discovered that some sixty-four[1] simple or as yet undecomposable bodies, called elements, in various proportions and compounds, constitute the accessible part of the crust. Of these, however, the great majority are comparatively of rare occurrence. The crust, so far as we can examine it, is mainly built up of about sixteen elements, which may be arranged in the two following groups, the most abundant bodies being placed first in each list:

Metalloids	At. Wt.	*Metals*	At. Wt.
Oxygen	15·96	Aluminium	27·30
Silicon	28·00	Calcium	39.90
Carbon	11·97	Magnesium	23·94
Sulphur	31·98	Potassium	39·04
Hydrogen	1·00	Sodium	22·99
Chlorine	35·37	Iron	55·90
Phosphorus	30·96	Manganese	54·80
Fluorine	19·10	Barium	136·80

The sixteen elements here mentioned form about ninety-nine parts of the earth's crust; the other elements constitute only about a hundredth part, though they include gold, sil-

[1] This number has within the last few years been increased by the alleged discovery of no fewer than fourteen new metals. Some of these bodies, however, have not yet been satisfactorily proved to be new. T. S. Humpidge, Nature, xxii. p. 232.

ver, copper, tin, lead, and the other useful metals, iron excepted. By far the most abundant and important element is Oxygen. It forms about 23 per cent by weight of air, 88·87 per cent of water, and about a half of all the rocks which compose the visible portion or crust of the globe. Another metalloid, Silicon, always united with oxygen, ranks next in abundance as a constituent of the crust. Of the remaining metalloids, Carbon and Sulphur sometimes occur in the free state, but more usually in combination. Chlorine (save perhaps at volcanic vents) does not occur in a free state, but is abundant in combination with the alkalies, especially with sodium. Fluorine is always found in combination, and has only recently been isolated by artificial chemical processes. It is the only element which has not been combined with oxygen. It chiefly occurs in union with Calcium as the mineral fluor-spar, and constitutes more than half of the mineral cryolite; but traces of its presence have been detected in other minerals, in sea-water, and in the bones, teeth, blood and milk of mammalia. Hydrogen occurs chiefly in combination with oxygen as the oxide, water, of which it forms 11·13 per cent by weight; also in combination with carbon as the hydrocarbons (mineral oils and gases), produced by the slow decomposition of organic matter. Phosphorus occurs with oxygen principally in calcic phosphate. Of the metals, a few are found in the native state (gold, silver, copper, etc), but those of importance in the framework of the earth's crust have entered into combination with metalloids or with each other. Putting the more important metals and metalloids together, we may compute that oxygen, silicon, aluminium, magnesium, calcium, potassium, sodium, iron and carbon, form together more than 97 per cent of the whole known crust.

So far as accessible to observation, the outer portion of our planet consists mainly of metalloids. Its metallic constituents have already in great part entered into combination with oxygen, so that the atmosphere contains the residue of that gas which has not yet united itself to terrestrial compounds. In a broad view of the arrangement of the chemical elements in the external crust, the suggestive speculation of Durocher deserves attention.[3] He regarded all rocks as referable to two layers or magmas coexisting in the earth's crust, the one beneath the other, according to their specific gravities. The upper or outer shell, which he termed the acid or siliceous magma, contains an excess of silica, and has a mean density of 2·65. The lower or inner shell, which he called the basic magma, has from six to eight times more of the earthy bases and iron-oxides, with a mean density of 2·96. To the former he assigned the early plutonic rocks, granite, felsite, etc., with the more recent trachytes; to the latter he relegated all the heavy lavas, basalts, diorites, etc. The ratio of silica is 7 in the acid magma to 5 in the basic. Though the proportion of silicic acid or of the earthy and metallic bases cannot be regarded as any certain evidence of the geological date of rocks, nor of their probable depth of origin, it is nevertheless a fact that (with many important exceptions) the eruptive rocks of the older geological periods are very generally super-silicated and of lower specific gravity, while those of later time are very frequently poor in silica, but rich in the earthy bases and in iron and manganese, with a consequent higher specific gravity. The latter, according to Durocher, have been forced up from a lower zone through the lighter sili-

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[3] Ann. des Mines, 1857. Translated by Haughton, "Manual of Geology," 1866, p. 16.

ceous crust. The sequence of volcanic rocks, as first announced by Richthofen, has an interesting connection with this speculation.[3]

The main mass of the earth's crust is composed of a few predominant compounds. Of these in every respect the most abundant and important is Silicon-dioxide or Silica (Kieselerde) SiO_2. As the fundamental ingredient of the mineral kingdom, it forms more than one-half of the known crust, which it seems to bind firmly together, entering as a main ingredient into the composition of most crystalline and fragmental rocks as well as into the veins that traverse them. It occurs in the free state as the abundant rock-forming mineral quartz, which strongly resists ordinary decay, and is therefore a marked constituent of many of the more enduring kinds of rock. As one of the acid-forming oxides (H_4SiO_4, Silicic acid, Kieselsäure) it forms combinations with alkaline, earthy, and metallic bases, which appear as the prolific and universally diffused family of the silicates. Moreover, it is present in solution in terrestrial and oceanic waters, from which it is deposited in pores and fissures of rocks. It is likewise secreted from these waters by abundantly diffused species of plants and animals (diatoms, radiolarians, etc.). It has been largely effective in replacing the organic textures of former organisms, and thus preserving them as fossils.

Alumina or aluminium-oxide (Thonerde), Al_2O_3, occurs sparingly as corundum, which, however, according to F. A. Genth, was the original condition of many now abundant complex aluminous minerals and rocks. The most common condition of aluminium is in union with silica. In this

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[3] *Postea*, Book III. Part I. Section i. § 5.

form it constitutes the basis of the vast family of the aluminous silicates, of which so large a portion of the crystalline and fragmental rocks consists. Exposed to the atmosphere, these silicates lose some of their more soluble ingredients, and the remainder forms an earth or clay consisting chiefly of silicate of aluminium.

Carbon is the fundamental element of organic life. In combination with hydrogen, as well as with oxygen, nitrogen and sulphur, it forms the various kinds of coal, and thus takes rank as an important rock-forming element. As carbon-dioxide, CO_2, it is present in the air, in rain, in the sea and in ordinary terrestrial waters. This oxide is soluble in water,[4] giving rise then to a dibasic acid termed Carbonic Acid (Kohlensäure), $CO(OH)_2$ or H_2CO , which forms carbonates, its combination with calcium having been instrumental in the formation of vast masses of solid rock. Carbon-dioxide constitutes a fifth part of the weight of ordinary limestone.

Sulphur (Soufre, Schwefel) occurs uncombined in occasional deposits like those of Sicily and Naples, to be afterward described, also in union with iron and other metals as sulphides; but its principal condition as a rock-builder is in combination with oxygen as sulphuric acid (Schwefelsäure), H_2SO_4, which forms sulphates of lime, magnesia, etc.

Calcium enters into the composition of many crystalline rocks in combination with silica and with other silicates. But its most abundant form is in union with carbon-dioxide, when it appears as the mineral, calcite ($CaCO_3$), or the rock, limestone. Calcium-carbonate, being soluble in water containing carbonic acid, is one of the most universally diffused

[4] One volume of water at 0° C. dissolves 1·7967 volumes of carbon-dioxide; at 15° C. the amount is reduced to 1·0020 volumes.

mineral ingredients of natural waters. It supplies the varied tribes of mollusks, corals, and many other invertebrates with mineral substance for the secretion of their tests and skeletons. Such too has been its office from remote geological periods, as is shown by the vast masses of organically-formed limestone, which enter so conspicuously into the structure of the continents. In combination with sulphuric acid, calcium forms important beds of gypsum and anhydrite.

Magnesium, Potassium, and Sodium play a less conspicuous but still essential part in the composition of the earth's crust. Magnesium, in combination with silica, forms a class of silicates of prime importance in the composition of volcanic and metamorphic rocks. As a carbonate, it unites with calcium-carbonate to form the widely diffused rock, dolomite. In union with chlorine, it takes a prominent place among the salts of sea-water. Potassium or Sodium, combined with silica, is present in small quantity in most silicates. In union with chlorine, as common salt, sodium is the most important mineral ingredient of sea-water, and can be detected in minute quantities in air, rain, and in terrestrial waters. In the old chemical formulæ hitherto employed in mineralogy the metals of the alkalies and alkaline earths are represented as oxides. Thus lime (calcium-monoxide), soda (sodium-monoxide), potash (potassium-monoxide), magnesia (magnesium-oxide), are denoted as in union with carbonic acid, sulphuric acid, silica, etc., forming carbonates, sulphates, silicates of lime, soda, etc.

Iron and Manganese are the two most common heavy metals, occurring both in the form of ores, and as constituents of rocks. Iron is the great pigment of nature. Its peroxide or sesquioxide, now known as ferric oxide, forms large mineral masses, and together with the protoxide or ferrous oxide, occurs in smaller or larger proportions in the great majority of crystalline rocks. Iron (as sulphate or in combination with organic acids) is removed in solution in the water of springs, and precipitated as a hydrous peroxide. Manganese is commonly associated with iron in minute proportions in igneous rocks, and being similarly removed in solution in water, is thrown down as bog manganese or wad.

Silicic Acid, Carbonic Acid, and Sulphuric Acid are the three acids with which most of the bases that compose the earth's crust have been combined. With these we may connect the water which, besides merely percolating through rocks, or existing inclosed in the vesicles of minerals, has been chemically absorbed in the process of hydration, and which thus constitutes more than 10 or even 20 per cent of some rocks (gypsum).

Chemical analysis has revealed the numerous combinations in which the elements are united to form minerals and rocks. Considerable additional light has been thrown on the subject by chemical synthesis, that is, by artificially producing the minerals and rocks which are found in nature. The experiments have been varied indefinitely so as to imitate as far as possible the natural conditions of production. Further reference to this subject will be found on pp. 161, 505 *et seq.*

Although every mineral may be made to yield data of more or less geological significance, only those minerals need be referred to here which enter as chief ingredients into the composition of rock-masses, or which are of frequent occurrence as accessories, and special note may be taken of those of their characters which are of main interest from a geological point of view, such as their modes of occurrence in relation to the genesis of rocks, and their weathering as indicative of the nature of rock-decomposition.

§ ii. Rock-forming Minerals

Minerals, as constituents of rocks, occur in four conditions, according to the circumstances under which they have been produced.

(1.) *Crystalline*, as (*a*) more or less regularly defined crystals, which, exhibiting the outlines proper to the mineral to which they belong, are said to be *idiomorphic*; (*b*) amorphous granules, aggregations or crystalloids, having an internal crystalline structure, in most cases easily recognizable with polarized light, as in the quartz of granite, and an external form which has been determined by contact with the adjacent mineral particles; such crystalline bodies which do not exhibit their proper crystalline outlines are said to be *allotriomorphic*; (*c*) "crystallites" or "microlites," incipient forms of crystallization, which are described on p. 205. The crystalline condition may arise from igneous fusion, aqueous solution, or sublimation.[5]

(2.) *Glassy* or *vitreous*, as a natural glass, usually including either crystals or crystallites, or both. Minerals have assumed this condition from a state of fusion, also from solution. The glass may consist of several minerals fused into one homogeneous substance. Where it has assumed a lithoid or stony structure, these component minerals crystallize out of the glassy magma, and may be recognized in various stages of growth (postea, pp. 194–214).

[5] For the microscopic characters of minerals and rocks, see p. 192.

(3.) *Colloid*, as a jelly-like though stony substance, deposited from aqueous solution. The most abundant mineral in nature which takes the colloid form is silica. Opal is a hardened colloidal condition of this substance. Chalcedony, doubtless originally colloidal silica, now unites the characters of quartz and opal, being only partially soluble in caustic potash and partially converted into a finely fibrous, doubly-refracting substance.

(4.) *Amorphous*, having no crystalline structure or form, and occurring in indefinite masses, granules, streaks, tufts, stainings, or other irregular modes of occurrence.

A mineral which has replaced another and has assumed the external form of the mineral so replaced, is termed a *Pseudomorph*. A mineral which incloses another has been called a *Perimorph*; one inclosed within another, an *Endomorph*.

Essential or accessory, original or secondary minerals.— A mineral is an essential ingredient when its absence would so alter the character of a rock as to make it something fundamentally different. The quartz of granite, for example, is an essential constituent of that rock, the removal of which would alter the petrographical species. A mineral is said to be accessory when its absence would not change the essential character of the rock. All essential minerals are original constituents of a rock, but all the original constituents are not essential. In granite, such minerals as topaz, beryl, and sphene often occur under circumstances which show that they crystallized out of the original magma of the rock. But they form so trifling a proportion in the total mass, and their absence would so little affect the general character of that mass, that they are regarded as accessory, though undoubtedly original and often important ingredients.[6] Again, in rocks of eruptive origin, the essential ingredients cannot be traced back further than the eruption of the mass containing them. They are not only original, as constituents of the lava, but are themselves original and non-derivative minerals, produced directly from the crystallization of molten minerals ejected from beneath the earth's crust, though, as Michel-Lévy has shown, the débris of older minerals may sometimes be traced amid the later crystals of massive rocks.[7] In rocks of aqueous origin, however, there are many, such as conglomerates and sandstones, where the component minerals, though original ingredients of the rocks, are evidently of derivative origin. The little quartz-granules of a sandstone have formed part of the rock ever since it was accumulated, and are its essential constituents. Yet each of these once formed part of some older rock, the destruction of which yielded materials for the production of the sandstone. The minute crystals of zircon, rutile, tourmaline and other minerals so often found in sands, clays, sandstones, shales and other sedimentary deposits, have been derived from the degradation of older crystalline rocks.

The same mineral may occur both as an original and as a secondary constituent. Quartz, for example, appears everywhere in both conditions; indeed, it may sometimes be found in a twofold form even in the same rock, though

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[6] Some of the "accessory" minerals may be of great importance as indicative of the conditions under which the rock was formed.

[7] Bull. Soc. Géol. France, 3d ser. iii. 199. See also Fouqué and Michel-Lévy, "Minéralogie Micrographique," p. 189. Some eruptive rocks abound in corroded or somewhat rounded or broken crystals which obviously have belonged to some previous state of consolidation. Such crystals, which are obviously more ancient than those forming the general mass of the rock, have been called *allogenic*, while those which belong to the time of formation of the rock, or to some subsequent change within the rock, are known as *authigenic*.

there is then usually some difference between the original and secondary quartz. A quartz-felsite, for instance, abounds in original little kernels, or in double pyramids of the mineral, often inclosing fluid cavities, while the secondary or accidental forms usually occur in veins, reticulations, or other irregular aggregates.

Accessory minerals frequently occur in cavities where they have had some room to crystallize out from the general mass. The "drusy" cavities, or open spaces lined with well-developed crystals, found in some granites are good examples, for it is there that the non-essential minerals are chiefly to be recognized. The veins of segregation found in many crystalline rocks, particularly in those of the granite series, are further illustrations of the original separation of mineral ingredients from the general magma of a rock (see Book IV. Part VII. § 3).

In some cases minerals assume a concretionary shape, which may be observed chiefly though not entirely in rocks formed in water. Some minerals are particularly prone to occur in concretions. Siderite (ferrous carbonate) is to be found in abundant nodules, mixed with clay and organic matter among consolidated muddy deposits. Calcite (calcium-carbonate) is likewise abundantly concretionary. Silica in the forms of chert and flint appears in irregular concretions, in calcareous formations, composed mainly of the remains of marine organisms.

Secondary minerals have been developed as the result of subsequent changes in rocks, and are almost invariably due to the chemical action of percolating water, either from above or from below. Occurring under circumstances in which such water could act with effect, they are found in cracks, joints, fissures and other divisional planes and cavities of rocks, especially in the minute interspaces between the component grains or minerals. Subterranean channels, frequently several feet or even yards wide, have been gradually filled up by the deposit of mineral matter on their sides (see the Section on Mineral Veins). The cavities formed by expanding steam in ancient lavas (amygdaloids) have offered abundant opportunities for deposits of this kind, and have accordingly been in large measure occupied by secondary minerals (amygdales), as calcite, chalcedony, quartz and zeolites.

In the subjoined list of the more important rock-forming minerals, attention is drawn mainly to those features that are of geological importance; the physical, chemical and microscopic characters of these minerals will be found in a text-book of mineralogy or petrography. Reference is therefore made here to features of more special significance to the geologist, such as modes of occurrence, whether original or secondary; modes of origin, whether igneous, aqueous, or organic; pseudomorphs, that is, the various minerals which any given mineral has replaced, while retaining their external forms, and likewise those which are found to have supplanted the mineral in question while in the same way retaining its form—a valuable clew to the internal chemical changes which rocks undergo from the action of percolating water (Book III. Part II. Section ii. §§ 1 and 2); and lastly, characteristics or peculiarities of weathering, where any such exist that deserve special mention.

1. Native elements are comparatively of rare occurrence, and only two of them, Carbon and Sulphur, occasionally play the part of noteworthy essential and accessory constituents of rocks. A few of the native metals, more

especially copper and gold, now and then appear in sufficient quantity to constitute commercially important ingredients of veins and rock-masses.

Graphite is found chiefly in ancient crystalline rocks, as gneiss, mica-schist, granite, etc.; some of the Laurentian limestones of Canada being so full of the diffused mineral as to be profitably worked for it; in rare instances coal has been observed changed into it by intrusive basalt (Ayrshire). In some cases graphite results from the alteration of imbedded organic matter, especially remains of plants; but its presence, and that of diamond, among ancient crystalline rocks and in meteorites can hardly be thus accounted for. Occasionally it is observed as a pseudomorph after calcite and pyrites, and sometimes inclosing sphene and other minerals.[8]

Sulphur occurs 1st, as a product of volcanic action in the vents and fissures of active and dormant cones. Volcanic sulphur is formed from the oxidation of the sulphuretted hydrogen, so copiously emitted with the steam that issues from volcanic vents, as at the Solfatara, near Naples. It may also be produced by the mutual decomposition of the same gas and anhydrous sulphuric acid. 2d, in beds and layers, or diffused particles, resulting from the alteration of previous minerals, particularly sulphates, or from deposit in water through decomposition of sulphuretted hydrogen. The frequent crystallization of sulphur shows that the mineral must have been formed at ordinary temperatures, for its natural crystals melt at 238·1° Fahr. Its formation may be observed in progress at many sulphureous springs, where it falls to the bottom as a pale mud through the oxidation of the sulphuretted hydrogen in the water. It occurs in Sicily, Spain and elsewhere, in beds of bituminous limestone and gypsum. These strata, sometimes full of remains of fresh-water shells and plants, are interlaminated with sulphur, the very shells being not infrequently replaced by this mineral. Here the presence of the sulphur may be traced to the reduction of the calcium-sulphate to the state of sulphide, through the action of the decomposing organic matter, and the subsequent production and decomposition of sulphuretted hydrogen, with consequent liberation of sulphur.[9] The sulphur deposits of Sicily furnish an excel-

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[8] Vom Rath. Sitzungsber. Wien. Akad. x. p. 67; Sullivan in Jukes' "Manual of Geology," 3d edit. (1872), p. 56.

[9] Braun, Bull. Soc. Géol. France, 1st ser. xii. p. 171.

lent illustration of the alternate deposit of sulphur and limestone. They consist mainly of a marly limestone, through which the sulphur is partly disseminated and partly interstratified in thin laminæ and thicker layers, some of which are occasionally 28 feet deep. Below these deposits lie older Tertiary gypseous formations, the decomposition of which has probably produced the deposits of sulphur in the overlying more recent lake basins.[10] The weathering of sulphur is exemplified on a considerable scale at these Sicilian deposits. The mineral, in presence of limestone, oxygen and moisture, becomes sulphuric acid, which, combining with the limestone, forms gypsum, a curious return to what was probably the original substance from the decomposition of which the sulphur was derived. Hence the site of the outcrop of the sulphur beds is marked at the surface by a white earthy rock, or borscale, which is regarded by the miners in Sicily to be a sure indication of sulphur underneath, as the gossan of Cornwall is indicative of underlying metalliferous veins.[11]

Iron, the most important of all the metals, is found only sparingly in the native state, in blocks which have fallen as meteorites, also in grains or dust inclosed in hailstones, in snow of the Alps, Sweden and Siberia, in the mud of the ocean-floor at remote distances from land, and in some eruptive rocks. There can be no doubt that a small but constant supply of native iron (cosmic dust) is falling upon the earth's surface from outside the terrestrial atmosphere.[12] This iron is alloyed with nickel, and contains small quantities of cobalt, copper and other ingredients. Dr. Andrews, however, showed in 1852 that native iron, in minute spicules or granules, exists in some basalts and other volcanic rocks[13] and Mr. J. Y. Buchanan has detected it in ap-

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[10] Memorie del R. Comitato Geologico d'Italia, i. (1871).

[11] Journ. Soc. Arts, 1873, p. 170. E. Ledoux, Ann. des Mines, 7me. sér. vii. p. 1. The Sicilian sulphur beds belong to the Oeningen stage of the Upper Tertiary deposits. They contain numerous plants and some insects. H. T. Geyler, Palæontographica, xxiii. Lief. 9, p. 317. Von Lasaulx, Neues Jahrb. 1879, p. 490.

[12] See Ehrenberg, Frorieps Notizen, Feb. 1846; Nordenskiöld, Comptes rendus, lxxvii. p. 463, lxxviii. p. 236. Tissandier, op. cit. lxxviii. p. 821, lxxx. p. 58, lxxxi. p. 576. See lxxv. (1872) p. 683. Yung, Bull. Soc. Vaudoise Sci. Nat. (1876), xiv. p. 493. Ranyard, Monthly Not. Roy. Astron. Soc. xxxix. (1879) p. 161. S. L. Phipson, Comptes rend. lxxxiii. p. 364. A Committee of the British Association was appointed in 1880 to investigate the subject of cosmic dust. See its reports for 1881–83.

[13] Brit. Assoc. Rep. 1852, postea, p. 768.

preciable quantity in the gabbro of the west of Scotland. It occurs also in the basalts of Bohemia and Greenland.[14]

In the great majority of cases the OXIDES occur combined with some acid. A few uncombined take a prominent place as essential constituents or frequent ingredients of rocks, especially the oxides of silicon and iron.

2. SILICA (SiO_2) is found in three chief forms, Quartz, Tridymite, and Opal.

Quartz is abundant as (1) an essential constituent of rocks, as in granite, gneiss, mica-schist, rhyolite (quartz-trachyte), quartz-porphyry, sandstone; (2) a secondary ingredient, wholly or partially filling veins, joints, cracks, and cavities. It has been produced from (*a*) igneous action, as in volcanic rocks; (*b*) aquo-igneous or plutonic action, as in granites, gneisses, etc.; (*c*) solution in water, as where it lines cavities or replaces other minerals. The last mode of formation is that of the crystallized quartz and chalcedony found as secondary ingredients in rocks.

The study of the endomorphs and pseudomorphs of quartz is of great importance in the investigation of the history of rocks. No mineral is so conspicuous for the variety of other minerals inclosed within it. In some secondary quartz-crystals, each prism forms a small mineralogical cabinet inclosing a dozen or more distinct minerals, as rutile, hæmatite, limonite, pyrites, chlorite, and many others.[15] Quartz may be observed replacing calcite, aragonite, siderite, gypsum, rock-salt, hæmatite, etc. This facility of replacement makes silica one of the most valuable

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[14] Nordenskiöld describes fifteen blocks of iron on the island of Disco, Greenland, the weight of the two largest being 21,000 and 8000 kilogrammes (20 and 8 tons, respectively). He observed that at the same locality, the underlying basalt contains lenticular and disk-shaped blocks of precisely similar iron, and inferred that the whole of the blocks may belong to a meteoric shower which fell during the time (Tertiary) when the basalt was poured out at the surface. He dismissed the suggestion that the iron could possibly be of telluric origin (Geol. Mag. ix. (1872) p. 462). But the microscope reveals in this basalt the presence of minute particles of native iron which, associated with viridite, are molded round the crystals of labradorite and augite (Fouqué and Michel-Lévy, op. cit. p. 443). Steenstrup, Daubrée, and others appear therefore to be justified in regarding this iron as derived from the inner metallic portions of the globe, which lie at depths inaccessible to our observations, but from which the vast Greenland basalt eruptions have brought up traces to the surface (K. J. T. Steenstrup, Vid. Medd. Nat. Foren. Copenhagen (1875) Nos. 16–19, p. 284; Zeitsch. Deutsch. Geol. Ges. xxviii. (1876) p. 225; Mineralog. Mag. July, 1884. F. Wöhler, Neues Jahrb. 1879, p. 832. Daubrée, Discours Acad. Sci. 1 March, 1880, p. 17. W. Flight, Geol. Mag. ii. (2d ser.) p. 152.

[15] See Sullivan, in Jukes' "Manual of Geology," 3d. edit. (1872), p. 61.

petrifying agents in nature. Organic bodies which have been silicified retain, often with the utmost perfection, their minutest and most delicate structures.

Quartz may usually be identified by its external characters, and especially by its vitreous lustre and hardness. When in the form of minute blebs or crystals, it may be recognized in many rocks with a good lens. Under the microscope, it presents a characteristic brilliant chromatic polarization, and in convergent light gives a black cross. Where it is an original and essential constituent of a rock, quartz very commonly contains minute rounded or irregular cavities or pores, partially filled with liquid. So minute are these cavities that a thousand millions of them may, when they are closely aggregated, lie within a cubic inch. The liquid is chiefly water, not uncommonly containing sodium chloride or other salt, sometimes liquid carbon-dioxide and hydrocarbons.[16] Chalcedony exhibits under the microscope a minute radial fibrous structure.

Rock-crystal and crystalline quartz resist atmospheric weathering with great persistence. Hence the quartz-grains may usually be easily discovered in the weathered crust of a quartziferous igneous rock. But corroded quartz-crystals have been observed in exposed mountainous situations, with their edges rounded and eaten away.[17] The chalcedonic and more or less soluble forms of silica are more easily affected. Flint and many forms of colored chalcedony weather with a white crust. But it is chiefly from the weathering of silicates (especially through the action of organic acids) that the soluble silica of natural waters is derived. (Book III. Part II. Section ii. § 7.)

Tridymite has been met with chiefly among volcanic rocks (trachytes, andesites, etc.), both as an abundant constituent of those which have been poured out in the form of lava, and also in ejected blocks (Vesuvius).[18]

Opal, a hydrous condition of silica formed from solution in water, is usually disseminated in veins and nests through rocks. Semi-opal occasionally replaces the original sub-

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[16] See Brewster, Trans. Roy. Soc. Edin. x. p. 1. Sorby, Quart. Journ. Geol. Soc. xiv. p. 453. Proc. Roy. Soc. xv. p. 153; xvii. p. 299. Zirkel, "Mikroskopische Beschaffenheit der Mineralien und Gesteine," p. 39. Rosenbusch, "Mikroskopische Physiographie," i. p. 30. Hartley, Journ. Chem. Soc. February, 1876. The occurrence of fluid-cavities in the crystals of rocks is more fully described in Part II. § iv. of this Book.

[17] Roth, Chem. Geol. i. p. 94.

[18] Vom Rath, Z. Deutsch. Geol. Ges. xxv. p. 236, 1873.

stance of fossil wood (wood-opal). Several forms of opal are deposited by geysers, and are known under the general appellation of sinters. Closely allied to the opals are the forms in which hydrous (soluble) silica appears in the organic world, where it constitutes the frustules of diatoms, the skeletons of radiolaria, etc. Tripoli powder (Kieselguhr), randanite, and other similar earths, are composed mainly or wholly of the remains of diatoms, etc.

Corundum, aluminium-oxide, is found in crystalline rocks, particularly in certain serpentines and schists, gneiss, granite, dolomite, and rocks of the metamorphic series.

3. Iron Oxides.—Four minerals, composed mainly of iron oxides, occur abundantly as essential and accessory ingredients of rocks. Hæmatite, Limonite, Magnetite, and Titanic iron.

Hæmatite (Fer oligiste, Rotheisen, Eisenglanz, Fe_2O_3= Fe70, O30) in the crystallized form occurs in veins, as well as lining cavities and fissures of rocks. The fibrous and more common form (which often has portions of its mass passing into the crystallized condition) lies likewise in strings or veins; also in cavities, which, when of large size, have given opportunity for the deposit of great masses of hæmatite, as in cavernous limestones (Westmoreland). It occurs with other ores and minerals as an abundant component of mineral veins, likewise in beds interstratified with sedimentary or schistose rocks. Scales and specks of opaque or clear bright red hæmatite, of frequent occurrence in the crystals of rocks, give them a reddish color or peculiar lustre (perthite, stilbite). Hæmatite appears abundantly as a product of sublimation in clefts of volcanic cones and lava streams. It is probably in most cases a deposition from water, resulting from the alteration of some previous soluble combination of the metal, such as the oxidation of the sulphate, and occurs in veins and beds, and as the earthy pigment that gives a red color to sandstones, clays and other rocks. It is found pseudomorphous after ferrous carbonate, and this has probably been the origin of beds of red ochre occasionally intercalated among stratified rocks. It likewise replaces calcite, dolomite, quartz, barytes, pyrites, magnetite, rock-salt, fluor-spar, etc.

Limonite (Brown iron-ore, $2Fe_2O_3+3H_2O=Fe_2O_3$ 85·56, H_2O 14·44) occurs in beds among stratified formations, and may be seen in the course of deposit, through the action of organic acids, on marsh-land (bog-iron-ore) and lake-bottoms. (Book IV. Part II. Section iii.) In the form of yellow ochre, it is precipitated from the waters of chalybeate springs containing green vitriol derived from the oxidation of iron-sulphides.[19] It is a common decomposition product in rocks containing iron among their constituents. It is thus always a secondary or derivative substance, resulting from chemical alteration. It is the usual pigment which gives tints of yellow, orange and brown to rocks. The pseudomorphous forms of limonite show to what a large extent combinations of iron are carried in solution through rocks. The mineral has been found replacing calcite, siderite, dolomite, hæmatite, magnetite, pyrite, marcasite, galena, blende, gypsum, barytes, fluor-spar, pyroxene, quartz, garnet, beryl, etc.

Magnetite (Fer oxydulé, Magneteisen, Fe_3O_4) occurs abundantly in some schists, in scattered octohedral crystals; in crystalline massive rocks like granite, in diffused grains or minute crystals; among some schists and gneisses (Norway and the Eastern States of North America), in massive beds; in basalt and other volcanic rocks, as an essential constituent, in minute octohedral crystals, or in granules or crystallites. It is likewise found as a pseudomorphous secondary product, resulting from the alteration of some previous mineral, as olivine, hæmatite, pyrite, quartz, hornblende, augite, garnet and sphene. It occurs with hæmatite, etc., as a product of sublimation at volcanic foci, where chlorides of the metals in presence of steam are resolved into hydrochloric acid and anhydrous oxides. It may thus result from either aqueous or igneous operations. It is liable to weather by the reducing effects of decomposing organic matter, whereby it becomes a carbonate, and then by exposure passes into the hydrous or anhydrous peroxide. The magnetite grains of basalt-rocks are very generally oxidized at the surface, and sometimes even for some depth inward.

Titanic Iron (Titaniferous Iron, Menaccanite, Ilmenite, Fer titané, Titaneisen $(FeTi)_2O_3$) occurs in scattered grains, plates and crystals as an abundant constituent of many crystalline rocks (basalt-rocks, diabase, gabbro and other igneous masses); also in veins or beds in syenite, serpentine and metamorphic rocks;[20] scarcely to be distinguished from magnetite when seen in small particles under the microscope, but possessing a brown semi-metallic lustre with re-

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[19] Sullivan, Jukes' "Manual of Geology," p. 63.

[20] Some of the Canadian masses of this mineral are 90 feet thick and many yards in length.

flected light; resists corrosion by acids when the powder of a rock containing it is exposed to their action, while magnetite is attacked and dissolved. Titanic iron frequently resists weathering, so that its black glossy granules project from a weathered surface of rock. In other cases, it is decomposed either by oxidation of its protoxide, when the usual brown or yellowish color of the hydrous ferric oxide appears, or by removal of the iron. The latter is believed to be the origin of a peculiar milky white opaque substance, frequently to be observed under the microscope, surrounding and even replacing crystals of titanic iron, and named Leucoxene by Gümbel.[21] In other cases the decomposition has resulted in the production of sphene.

Chromite ($FeCr_2O_4$) occurs in black opaque grains and crystals not infrequently in altered olivine-rocks.

Spinels, a group of minerals, may be taken here. They are closely related to each other, having cubic forms and varying in composition from *magnetite* (see above) at the one end to *spinel* ($MgAl_2O_4$) at the other. They are not infrequent as minute grains or crystals in some igneous and metamorphic rocks. Between magnetite and spinel come intermediate varieties, as *chromite* (see above), *Picotite*, *Hercynite* and *Pleonaste*.

4. Manganese Oxides are frequently associated with those of iron in ordinary rock-forming minerals, but in such minute proportions as to have been generally neglected in analyses. Their presence in the rocks of a district is sometimes shown by deposits of the hydrous oxide in the forms of Psilomelane ($H_2MnO_4+H_2O$) and Wad ($MnO_2+MnO+H_2O$). These deposits sometimes take place as black or dark brown branching, plant-like or *dendritic* impressions between the divisional planes of close-grained rocks (limestone, felsite, etc.), sometimes as accumulations of a black or brown earthy substance in hollows of rocks, occasionally as deposits in marshy places, like those of bog-iron-ore, and abundantly on some parts of the sea-floor. (See p. 769.)

5. Silicates.—These embrace by far the largest and most important series of rock-forming minerals. Their chief groups are the anhydrous aluminous and magnesian silicates embracing the Felspars, Hornblendes, Augites,

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[21] "Die Paläolitische Eruptivgesteine des Fichtelgebirges," 1874, p. 29. See Rosenbusch, Mik. Physiog. ii. p. 336. De la Vallée Poussin and Renard, Mém. Couronnées Acad. Roy. de Belgique, 1876, xl. Plate vi. pp. 34 and 35. Fouqué and Michel-Lévy, "Minéralogie Micrograph," p. 426. See postea, p. 1040.

Micas, etc., and the hydrous silicates which include the Zeolites, Clays, talc, chlorite, serpentine, etc.

The family of the Felspars forms one of the most important of all the constituents of rocks, seeing that its members constitute by much the largest portion of the plutonic and volcanic rocks, are abundantly present among many crystalline schists, and by their decay have supplied a great part of the clay out of which argillaceous sedimentary formations have been constructed.

The felspars are usually divided into two series. 1st, The orthoclastic or monoclinic felspars, consisting of two species or varieties, Orthoclase and Sanidine; and, 2d, The plagioclastic or triclinic felspars, among which, as constituents of rocks, may be mentioned the species albite, anorthite, oligoclase, andesine, labradorite, and microcline.

Orthoclase (K_2O 16·89, Al_2O_3 18·43, SiO_2 64·68) occurs abundantly as an original constituent of many crystalline rocks (granite, syenite, felsite, gneiss, etc.), likewise in cavities and veinings in which it has segregated from the surrounding mass (pegmatite); seldom found in unaltered sedimentary rocks except in fragments derived from old crystalline masses; generally associated with quartz, and often with hornblende, while the felspars less rich in silica more rarely accompany free quartz. It is an original constituent of plutonic and old volcanic rocks (granite, felsite, etc.), and of gneiss and various schists. A few examples have been noticed where it has replaced other minerals (prehnite, analcime, laumontite). Under the microscope it is recognizable from quartz by its characteristic rectangular forms, cleavage, twinning, angle of extinction, turbidity, and frequent alteration.[22] Orthoclase weathers on the whole with comparative rapidity, though durable varieties are known. The alkali and some of the silica are removed, and the mineral passes into clay or kaolin (p. 140).

Sanidine, the clear glassy fissured variety of orthoclase so conspicuous in the more silicated Tertiary and modern lavas, occurs in some trachytes in large flat tables (hence the name "sanidine"); more commonly in fine clear or gray crystals or crystalline granules; an eminently volcanic mineral.

Plagioclase (Triclinic) Felspars.—While the different felspars which crystallize in the triclinic system may be more or less

[22] On microscopic determination of felspars, see Fouqué and Michel-Lévy, op. cit. pp. 209, 227, and postea, pp. 168–172.

easily distinguished in large crystals or crystalline aggregates, they are difficult to separate in the minute forms in which they commonly occur as rock constituents. They have been grouped by petrographers under the general name Plagioclase (with oblique cleavage), proposed by Tschermak, who regards them as mixtures in various proportions of two fundamental compounds—albite or soda-felspar, and anorthite or lime-felspar.

They occur mostly in well-developed crystals, partly in irregular crystalline grains, crystallites or microlites. On a fresh fracture, their crystals often appear as clear glassy strips, on which may usually be detected a fine parallel lineation or ruling, indicating a characteristic polysynthetic twinning which never appears in orthoclase. A felspar striated in this manner can thus be at once pronounced to be a triclinic form, though the distinction is not invariably present. Under the microscope, the fine parallel lamellation or striping, best seen with polarized light, forms one of the most distinctive features of this group of felspars. The chief triclinic felspars are, Microcline (potash-felspar, $K_2Al_2Si_6O_{16}$), which occurs in granites, particularly as the common felspar of the graphic varieties; also in some gneisses, etc.; Albite (soda-felspar, Na_2O 11·82, Al_2O_3 18·56, Si_2O 68·62), found in some granites, and in several volcanic rocks; Oligoclase (soda-lime and lime-soda felspars, Na_2O 8·2, CaO 4·8, Al_2O_3 23·0, SiO_2 62·8) occurs in many granites and other eruptive rocks; Andesine (Na_2O 7·7, CaO 7·0, Al_2O_3 25·6, SiO_2 60·0), observed in some syenites, etc.; Labradorite (Na_2O 4·6, CaO 12·4, Al_2F_3 30·2, SiO_2 52·9), an essential constituent of many lavas, etc., abundant in masses in the azoic rocks of Canada, etc.; Anorthite (lime-felspar, CaO 20·10, Al_2O_3 36·82, SiO_2 43·08) found in many volcanic rocks, sometimes in granites and metamorphic rocks.

The triclinic felspars have been produced sometimes directly from igneous fusion, as can be studied in many lavas, where often one of the first minerals to appear in the devitrification of the original molten glass has been the labradorite or other plagioclase. In other cases, they have resulted from the operation of the processes to which the formation of the crystalline schists was due; large beds as well as abundant diffused strings, veinings, and crystals of triclinic felspar (labradorite) form a marked feature among the ancient gneisses of Eastern Canada. The more highly silicated species (albite, oligoclase) occur with orthoclase as essential constituents of many granites and other plutonic rocks. The more basic forms (labradorite, anorthite) are generally absent where free silica is present; but occur in the more basic igneous rocks (basalts, etc.).

Considerable differences are presented by the triclinic felspars in regard to weathering. On an exposed face of rock they lose their glassy lustre and become white and opaque. This change, as in orthoclase, arises from loss of bases and silica, and from hydration. Traces of carbonates may often be observed in weathered crystals. The original steam cavities of old volcanic rocks have generally been filled with infiltrated minerals, which in many cases have resulted from the weathering and decomposition of the triclinic felspars. Calcite, prehnite, and the family of zeolites have been abundantly produced in this way. The student will usually observe that where these minerals abound in the cells and crevices of a rock, the rock itself is for the most part proportionately decomposed, showing the relation that subsists between infiltration-products and the decomposition of the surrounding mass. Abundance of calcite in veins and cavities of a felspathic rock affords good ground for suspecting the presence in the latter of a lime-felspar.[23] (See under "Albitization," postea, p. 1040.)

Saussurite, formerly described as a distinct mineral species, is now found to be the result of the decomposition of felspars, which have thus acquired a dull white aspect and contain secondary crystallizations (zoisite) out of the decomposed substance of the original felspar. Such saussuritic felspars occur in varieties of gabbro and diorite. Under the microscope they present a confused aggregate of crystalline needles and granules imbedded in an amorphous matrix. (See postea, p. 1040.)

Leucite (K_2O 21·53, Al_2O_3 23·50, SiO_2 54·97) is a markedly volcanic mineral, occurring as an abundant constituent of many ancient and modern Italian lavas, and in some varieties of basalt. Under the microscope, sections of this mineral are eight-sided or nearly circular, and very commonly contain inclosures of magnetite, etc., conforming in arrangement to the external form of the crystal or disposed radially.

Nepheline (Na_2O 17·04, Al_2O_3 35·26, K_2O 6·46, SiO_2 41·24), essentially a volcanic mineral, being an abundant constit-

[23] A valuable essay on the stages of the weathering of triclinic felspar as revealed by the microscope was published by G. Rose in 1867. Zeitsch. Deutsch. Geol. Ges. xix. p. 276.

uent of phonolite, of some Vesuvian lavas, and of some forms of basalt, presents under the microscope various six-sided and even four-sided forms, according to the angles at which the prisms are cut.[24] Under the name of *Elæolite* are comprised the greenish or reddish, dull, greasy-lustred, compact or massive varieties of nepheline, which occur in some syenites and other ancient crystalline rocks.

THE MICA FAMILY embraces a number of minerals, distinguished especially by their very perfect basal cleavage, whereby they can be split into remarkably thin elastic laminæ, and by a predominant splendent pearly lustre. They consist essentially of silicates of alumina, magnesia, iron and alkalies, and may be conveniently divided into two groups, the *white micas*, which are silicates of alumina with alkalies, iron and magnesia, and the *black micas*, in which the magnesia and iron play a more conspicuous part.

Muscovite (Potash-mica, white mica, Glimmer, K_2O 3·07–12·44, Na_2O 0–4·10, FeO 0–1·16, Fe_2O_3 0·46–8·80, MgO 0·37–3·08, Al_2O_3 28·05–38·41, SiO_2 43·47–51·73, H_2O 0·98–6·22), abundant as an original constituent of many crystalline rocks (granite, etc.), and as one of the characteristic minerals of the crystalline schists; also in many sandstones, where its small parallel flakes, derived, like the surrounding quartz grains, from older crystalline masses, impart a silvery or "micaceous" lustre and fissility to the stone.[25] The persistence of muscovite under exposure to weather is shown by the silvery plates of the mineral, which may be detected on a crumbling surface of granite or schist where most of the other minerals, save the quartz, have decayed; also by the frequency of the micaceous lamination of sandstones.

Biotite (Magnesia-mica, black mica, MgO 10–30 per cent) occurs abundantly as an original constituent of many granites, gneisses, and schists; also sometimes in basalt, trachyte, and as ejected fragments and crystals in tuff. Its small scales, when cut transverse to the dominant cleavage, may usually be detected under the microscope by their remarkably strong dichroism, their fine parallel lines of cleavage, and their frequently frayed appearance at the ends. Under the action of the weather it assumes a pale, dull, soft

[24] On the microscopic distinction between nepheline and apatite, see Fouqué and Michel-Lévy, "Minéral. Micrograph." p. 276.

[25] On the microscopic determination of the micas, see Fouqué and Michel-Lévy, op. cit. p. 333.

crust, owing to removal of its bases. The mineral *rubellan*, which occurs in hexagonal brown or red opaque inelastic tables in some basalts and other igneous rocks, is regarded as an altered form of biotite.

Phlogopite is another dark ferro-magnesian mica which contains a little fluorine. *Lepidolite* (Lithia-mica) occurs in some granites and crystalline schists, especially in veins. *Damourite*, merely a variety of muscovite, occurs among crystalline schists. *Sericite*, a talc-like variety of muscovite, occurs in soft inelastic scales in many schists, as a result of the alteration of orthoclase felspar.[26] *Margarodite*, a silvery talc-like hydrous mica, is widely diffused as a constituent of granite and other crystalline rocks. *Paragonite*, a scaly micaceous mineral, forms the main mass of certain alpine schists.

Hornblende (Monoclinic Amphibole, CaO_2 10–12, MgO 11–24, Fe_2O_3 0–10, Al_2O_3 5–18, SiO_2 40–50 also usually with some Na_2O, K_2O and FeO). Divided into two groups. 1st. Non-aluminous, including the white and pale green or gray fibrous varieties (tremolite, actinolite, etc.). 2d. Aluminous, embracing the more abundant dark green, brown, or black varieties. Under the microscope, hornblende presents cleavage-angles of 124° 30′, the definite cleavage-planes intersecting each other in a well-marked lattice work, sometimes with a finely fibrous character superadded. It also shows a marked pleochroism with polarized light, which, as Tschermak first pointed out, usually distinguishes it from augite.[27] Hornblende has abundantly resulted from the alteration (paramorphism) of augite (see below, Uralite). In many rocks the ferro-magnesian silicate which is now hornblende was originally augite; the epidiorites, for instance, were probably once dolerites or allied pyroxenic rocks. The pale non-aluminous hornblendes are found among gneisses, crystalline limestones, and other metamorphic rocks. The dark varieties, though also found in similar situations, sometimes even forming entire masses of rock (amphibolite, hornblende-rock, hornblende-schist), are the common forms in granitic and volcanic rocks (syenite, diorite, hornblende-andesite, etc.). The former group naturally gives rise by weathering to various

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[26] On the occurrence of this mineral in schists, see Lossen, Zeitsch. Deutsch. Geol. Ges. 1867, pp. 546, 661.

[27] Wien. Acad. May, 1869. See also Fouqué and Michel-Lévy, op. cit. pp. 349, 365.

hydrous magnesian silicates, notably to serpentine and talc. In the weathering of the aluminous varieties, silica, lime, magnesia, and a portion of the alkalies are removed, with conversion of part of the earths and the iron into carbonates. The further oxidation of the ferrous carbonate is shown by the yellow and brown crust so commonly to be seen on the surface or penetrating cracks in the hornblende. The change proceeds until a mere internal kernel of unaltered mineral remains, or until the whole has been converted into a ferruginous clay.

Anthophyllite (Rhombic Amphibole $(MgFe)SiO_3$) is a mineral which occurs in bladed, sometimes rather fibrous forms, among the more basic parts of old gneisses; also in zones of alteration round some of the ferro-magnesian minerals of certain gabbros.

Soda-amphiboles resemble ordinary hornblende, but, as their name denotes, they contain a more marked proportion of soda. They include a blue variety called *Glaucophane*, which is found abundantly in certain schists; *Riebeckite*, which is also blue and occurs in some granites and micro-granites; *Arfvedsonite*, a dark greenish or brown variety.

Uralite is the name given to a mineral which was originally pyroxene, but has now by a process of paramorphism acquired the internal cleavage and structure of hornblende (amphibole). Under the microscope a still unchanged kernel of pyroxene may in some specimens be observed in the centre of a crystal surrounded by strongly pleochroic hornblende, with its characteristic cleavage and actinolitic needles (postea, p. 1040). *Smaragdite* is a beautiful grass-green variety also resulting from the alteration of a pyroxene.

Augite (Monoclinic Pyroxene, CaO 12–27·5, MgO 3–22·5, FeO 1–34, Fe_2O_3 0–10, Al_2O_3 0–11; SiO_2 40–57·4). Divided like hornblende into two groups. 1st. Non-aluminous, with a prevalent green color (malacolite, coccolite, diopside, sahlite, etc.). 2d. Aluminous, including generally the dark green or black varieties (common augite, fassaite). It would appear that the substance of hornblende and augite is dimorphous, for the experiments of Berthier, Mitscherlich and G. Rose showed that hornblende, when melted and allowed to cool, assumed the crystalline form of augite; whence it has been inferred that hornblende is the result of slow, and augite of comparatively rapid cooling.[28] Under

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[28] The same results have been obtained recently by Fouqué and Michel-Lévy, "Synthèse des Minéraux et des Roches," 1882, p. 78.

the microscope, augite in thin slices is only very feebly pleochroic, and presents cleavage lines intersecting at an angle of 87° 5′. It is often remarkable for the amount of extraneous materials inclosed within its crystals. Like some felspars, augite may be found in basalt with merely an outer casing of its own substance, the core being composed of magnetite, of the ground-mass of the surrounding rock, or of some other mineral (Fig. 7). The distribution of augite resembles that of hornblende; the pale, non-aluminous varieties are more specially found among gneisses, marbles, and other crystalline, foliated, or metamorphic rocks; the dark-green or black varieties enter as essential constituents into many igneous rocks of all ages, from Palæozoic up to recent times (diabase, basalt, andesite, etc.). Its weathering also agrees with that of hornblende. The aluminous varieties, containing usually some lime, give rise to calcareous and ferruginous carbonates, from which the fine interstices and cavities of the surrounding rock are eventually filled with threads and kernels of calcite and strings of hydrous ferric oxide. In basalt and dolerite, for example, the weathered surface often acquires a rich yellow color from the oxidation and hydration of the ferrous oxide.

Omphacite, a granular variety of pyroxene, grass green in color, and commonly associated with red garnet in the rock known as eclogite.

Diallage, a variety of augite, characterized by its somewhat metallic lustre and foliated aspect, is especially a constituent of gabbro.

Rhombic-Pyroxenes. — There are three rhombic forms of pyroxene, which occur as important constituents of some rocks, Enstatite, Bronzite and Hypersthene. *Enstatite* occurs in lherzolite, serpentine, and other olivine rocks; also in meteorites. *Bronzite* is found under similar conditions to enstatite, from which it is with difficulty separable. It occurs in some basalts and in serpentines; also in meteorites. Bronzite and enstatite weather into dull green serpentinous products. *Bastite* or Schiller-spar is a frequent product of the alteration of Bronzite or Enstatite, and may be observed with its characteristic pearly lustre in serpentine. *Hypersthene* occurs in hypersthenite and hypersthene-andesite; also associated with other magnesian minerals among the crystalline schists.

Olivine (Peridot, MgO 32·4–50·5, FeO 6–29·7, SiO_2 31·6–42·8) forms an essential ingredient of basalt, likewise the main part of various so-called olivine-rocks or peridotites (as lherzolite and pikrite), and occurs in many gabbros; under the microscope with polarized light, gives, when fresh, bright colors, specially red and green, but it is not perceptibly pleochroic. Its orthorhombic outlines can sometimes be readily observed, but it often occurs in irregularly shaped granules or in broken crystals, and is liable to be traversed by fine fissures, which are particularly developed transverse to the vertical axis. It is remarkably prone to alteration. The change begins on the outer surface and extends inward and specially along the fissures, until the whole is converted either into a green granular or fibrous substance, which is probably in most cases serpentine (Fig. 26), or into a reddish-yellow amorphous mass (limonite).

Hauyne (SiO_2 34·06, Al 27·64, Na_2O 11·79, K_2O 4·96, CaO 10·60, SO_4 11·25) occurs abundantly in Italian lavas, in basalt of the Eifel, and elsewhere.

Nosean (SiO_2 33·79, Al 28·75, Na_2O 26·20, SO_4 11·26), under the microscope, is one of the most readily recognized minerals, showing a hexagonal or quadrangular figure, with a characteristic broad dark border corresponding to the external contour of the crystal, and where weathering has not proceeded too far, inclosing a clear colorless centre. It occurs in minute forms in most phonolites, also in large crystals in some sanidine volcanic rocks. Both hauyne and nosean are volcanic minerals associated with the lavas of more recent geological periods.

Epidote (Pistacite, CaO 16–30, MgO 0–4·9, Fe_2O_3 7·5–17·24, Al_2O_3 14·47–28·9, SiO_2 33·81–57·65) occurs in many crystalline rocks, as a result of the alteration of other silicates such as felspars and hornblende (see postea, p. 1040); largely distributed in certain schists and quartzites, sometimes associated with beds of magnetite and hæmatite.

Zoisite is allied to epidote but contains no iron. It occurs in altered basic igneous rocks and also (sometimes in large aggregations) in metamorphic groups.

Vesuvianite (Idocrase, CaO 27·7–37·5, MgO 0–10·6, FeO 0–16, Al_2O_3 10·5–26·1, SiO_2 35–39·7, H_2O 0–2·73) occurs in ejected blocks of altered limestone at Somma, also among crystalline limestones and schists.

Andalusite (Al_2O_3 50·96–62·2, Fe_2O_3 0–5·7, SiO_2 35·3–40·17).—Found in crystalline schists. The variety *Chiastolite*, abundant in some dark clay-slates, is distinguished by the regular manner in which the dark substance of the surrounding matrix has been inclosed, giving a cross-like transverse section. These crystals have been developed in the rock after its formation, and are regarded as proofs of contact-metamorphism. (Book IV. Part VIII.) *Sillimanite* or *Fibrolite* is the name given to a fibrous variety which is not infrequent among schistose rocks.

Dichroite (Cordierite, Iolite, MgO 8·2–20·45, FeO 0–11·58, Al_2O_3 28·72–33·11, SiO_2 48·1–50·4, H_2O 0–2·66) occurs in gneiss, sometimes in large amount (cordierite-gneiss); occasionally as an accessory ingredient in some granites; also in talc-schist. Undergoes numerous alterations, having been found changed into pinite, chlorophyllite, mica, etc.

Scapolites, a series of minerals consisting of silicates of alumina, lime and soda, with a little chlorine. They are found among the cavities of lavas, but more frequently among metamorphic rocks, where they appear in association with altered felspars. *Dipyre*, *Couseranite* and *Meionite* are varieties of the series.

Kyanite (Al_2SiO_5) occurs in bladed aggregates of a beautiful delicate blue color among schistose rocks; also in granular forms.

Garnet (CaO 0–5·78, MgO 0–10·2, Fe_2O_3 0–6·7, FeO 24·82–39·68, MnO 0–6·43, Al_2O_3 15·2–21·49, SiO_2 35·75–52·11.—The common red and brown varieties occur as essential constituents of eclogite, garnet-rock; and often as abundant accessories in mica-schist, gneiss, granite, etc. Under the microscope, garnet as a constituent of rocks, presents three-sided, four-sided, six-sided, eight-sided (or even rounded) figures according to the angle at which the individual crystals are cut; it is usually clear, but full of flaws or of cavities; passive in polarized light.

Tourmaline (Schorl, CaO 0–2·2, MgO 0–14·89, Na_2O 0–4·95, K_2O 0–3·59, FeO 0–12, Fe_2O_3 0–13·08, Al_2O_3 30·44–44·4, SiO_2 35·2–41·16, B 3·63–11·78, F 1·49–2·58), with quartz, forms tourmaline-rock; associated with some granites; occurs also diffused through many gneisses, schists, crystalline limestones, and dolomites, likewise in sands (see Zircon). Pleochroism strongly marked.

Zircon (ZrO_2 63·5–67·16, Fe_2O_3 0–2, SiO_2 32–35·26) occurs as a chief ingredient in the zircon-syenite of Southern Norway; frequent in granites, diorites, gneisses, crystalline limestones and schists; in eclogite; as clear red grains in some basalts, and also in ejected volcanic blocks; of common occurrence in sands, clays, sandstones, shales and other sedimentary rocks derived from crystalline masses such as granite, etc.

Titanite (Sphene, CaO 21·76–33, TiO_2 33–43·5, SiO_2 30–35), dispersed in small characteristically lozenge-shaped crystals in many syenites, also in granite, gneiss, and in some volcanic rocks (basalt, trachyte, phonolite).

Zeolites.—Under this name is included a characteristic family of minerals, which have resulted from the alteration, and particularly from the hydration, of other minerals, especially of felspars. Secondary products, rather than original constituents of rocks, they often occur in cavities both as prominent amygdales and veins, and in minute interstices only perceptible by the microscope. In these minute forms they very commonly present a finely fibrous divergent structure. As already remarked, a relation may often be traced between the containing rock and its inclosed zeolites. Thus among the basalts of the Inner Hebrides, the dirty green decomposed amygdaloidal sheets are the chief repositories of zeolites, while the firm, compact, columnar beds are comparatively free from these alteration products.[29] Among the more common zeolites are *Analcime*, *Natrolite*, *Prehnite* and *Stilbite*.

Kaolin (Al_2O_3 38·6–40·7, CaO 0–3·5, K_2O 0–1·9, SiO_2 45·5–46·53, H_2O 9–14·54) results from the alteration of potash- and soda-felspars exposed to atmospheric influences. Under the microscope the fine white powdery substance is found to include abundant minute six-sided colorless plates and scales which have been formed by recrystallization of the decomposed substance of the felspar. The purest white kaolin is called *china-clay*, from its extensive use in the manufacture of porcelain. Ordinary clay is impure from admixture of iron, lime, and other ingredients, among which the débris of the undecomposed constituents of the original rock may form a marked proportion.

Talc (MgO 23·19–35·4, FeO 0–4·5, Al_2O_3 0–5·67, SiO_2 56·62–64·53, H_2O 0–6·65) occurs as an essential constituent of talc-schist, and as an alteration product replacing mica, hornblende, augite, olivine, diallage, and other minerals in crystalline rocks.

Chlorite (MgO 24·9–36, FeO 0–5·9, Fe_2O_3 0–11·36, Al_2O_3 10·5–19·9, SiO_2 30–33·5, H_2O 11·5–16), including several varieties or species, occurs in small green hexagonal tables or scaly vermicular or earthy aggregates; is an essential ingredient of chlorite-schist, and occurs abundantly as an alteration product (of hornblende, etc.) in fine filaments, incrustations, and layers in many crystalline rocks. (See

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[29] See Sullivan in Jukes' "Manual of Geology," p. 85.

under "Chloritization," *postea*, p. 1040.) Among the minerals grouped under the general head of chlorites are *Chlorophæite*, *Clinochlore*, *Delessite*, *Pennine*, *Ripidolite*, and others.

Ottrelite (Chloritoid, H_2O (FeMg) Al_2SiO_7) occurs in small lustrous iron-black or greenish-black lozenge-shaped or six-side plates in certain schists. It resembles chlorite but is at once distinguishable from that mineral by its much greater hardness.

Serpentine (MgO 28–43, FeO 1–10·8, Al_2O_3 0–5·5, SiO_2 37·5–44·5, H_2O 9·5–14·6) is a product of the alteration of pre-existing minerals, and especially of olivine. It occurs in nests, grains, threads, and veins in rocks which once contained olivine[30] (p. 138), also massive as a rock, in which it has replaced olivine, enstatite or some other magnesian bisilicate (pp. 300, 1040). Under the microscope it presents, in very thin slices, a pale leek-green or bluish-green base, showing aggregate polarization. Through this base runs a network of dark opaque threads and veinings. Sometimes among these veinings, or through the network of green serpentinous matter in the base, the forms of original olivine crystals may be traced (Figs. 26, 27).

Glauconite (CaO *0–4·9*, MgO *0–5·9*, K_2O *0–12·9*, Na_2O *0–2·5*, FeO 3–25·5, Fe_2O_3 0–28·1, Al_2O_3 1·5–13·3, SiO_2 46·5–60·09, H_2O 0–14·7). Found in many stratified formations, particularly among sandstones and limestones, where it envelops grains of sand, or fills and coats foraminifera and other organisms, giving a general green tint to the rock. It is at present being formed on the sea-floor off the coasts of Georgia and South Carolina, where Pourtales found it filling the chambers of recent polythalamia.

6. CARBONATES. This family of minerals furnishes only four which enter largely into the formation of rocks, viz. Carbonate of Calcium in its two forms, Calcite and Aragonite, Carbonate of Magnesium (and Calcium) in Dolomite, and Carbonate of Iron in Siderite.

Calcite ($CaCO_3$) occurs as (1) an original constituent of many aqueous rocks (limestone, calcareous shale, etc.), either as a result of chemical deposition from water (calc-sinter, stalactites, etc.), or as a secretion by plants or animals;[31] or (2) as a secondary product resulting from weath-

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[30] See Tschermak, Wien. Akad. lvi. 1867.

[31] Mr. Sorby has investigated the condition in which the calcareous matter of the harder parts of invertebrates exists. He finds, that in foraminifera, echinoderms, brachiopods, crustacea, and some lamellibranchs and gasteropods,

ering, when it is found filling or lining cavities, or diffused through the capillary interstices of minerals and rocks. It probably never occurs as an original ingredient in the massive crystalline rocks, such as granite, felsite, and lavas. Under the microscope, calcite is readily distinguishable by its intersecting cleavage lines, by a frequent twin lamellation (sometimes giving interference colors), strong double refraction, weak or inappreciable pleochroism, and characteristic iridescent polarization tints of gray, rose and blue.

From the readiness with which water absorbs carbon-dioxide, from the increased solvent power which it thereby acquires, and from the abundance of calcium in various forms among minerals and rocks, it is natural that calcite should occur abundantly as a pseudomorph replacing other minerals. Thus, it has been observed taking the place of a number of silicates, as orthoclase, oligoclase, garnet, augite and several zeolites; of the sulphates, anhydrite, gypsum, barytes, and celestine; of the carbonates, aragonite, dolomite, cerussite; of the fluoride, fluor-spar; and of the sulphide, galena. Moreover, in many massive crystalline rocks (diorite, dolerite, etc.), which have been long exposed to atmospheric influence, this mineral may be recognized by the brisk effervescence produced by a drop of acid, and in microscopic sections it appears filling the crevices, or sending minute veins among the decayed mineral constituents. Calcite is likewise the great petrifying medium: the vast majority of the animal remains found in the rocky crust of the globe have been replaced by calcite, sometimes with a complete preservation of internal organic structure, sometimes with a total substitution of crystalline material for that structure, the mere outer form of the organism alone surviving.[32]

Aragonite ($CaCO_3$), harder, heavier, and much less abundant than calcite, which is the more stable form of calcium-carbonate; occurs with beds of gypsum, also in mineral veins, in strings running through basalt and other igneous rocks, and in the shells of many mollusca. It is thus always a deposit from water, sometimes from warm mineral springs, sometimes as the result of the internal alteration of rocks,

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it occurs as calcite; that in nautilus, sepia, most gasteropods, many lamellibranchs, etc., it is aragonite; and that in not a few cases the two forms occur together, or that the carbonate of lime is hardened by an admixture of phosphate. Quart. Journ. Geol. Soc. 1879. Address, p. 61.

[32] See index sub voc. Calcite.

and sometimes through the action of living organisms. Being more easily soluble than calcite, it has no doubt in many cases disappeared from limestones originally formed mainly of aragonite shells, and has been replaced by the more durable calcite, with a consequent destruction of the traces of organic origin. Hence what are now thoroughly crystalline limestones may have been formed by a slow alteration of such shelly deposits (p. 811).

Dolomite (Bitter-spar (Ca; Mg)CO_3, p. 264) occurs (1) as an original deposit in massive beds (magnesian limestone), belonging to many different geological formations; (2) as a product of alteration, especially of ordinary limestone or of aragonite (Dolomitization, p. 546).

Siderite (Brown Ironstone, Spathic Iron, Chalybite, Ferrous Carbonate, $FeCO_3$) occurs crystallized in association with metallic ores, also in beds and veins of many crystalline rocks, particularly with limestones; the compact argillaceous varieties (clay-ironstone) are found in abundant nodules and beds in the shales of Carboniferous and other formations where they have been deposited from solution in water in presence of decaying organic matter (see pp. 257, 267).

7. SULPHATES. Among the sulphates of the mineral kingdom, only two deserve notice here as important compounds in the constitution of rocks—viz. calcium-sulphate or sulphate of lime in its two forms, Anhydrite and Gypsum; and barium-sulphate or sulphate of baryta in Barytes.

Anhydrite ($CaSO_4$) occurs more especially in association with beds of gypsum and rock-salt (see p. 265).

Gypsum (Selenite, $CaSO_4+2H_2O$). Abundant as an original aqueous deposit in many sedimentary formations (see p. 265).

Barytes (Heavy Spar, $BaSO_4$). Frequent in veins and especially associated with metallic ores as one of their characteristic vein-stones.

8. PHOSPHATES. The phosphates which occur most conspicuously as constituents or accessory ingredients of rocks are the tricalcic phosphate or Apatite, and triferrous phosphate or Vivianite.

Apatite ($3Ca_3(PO_4)+CaF_2$) occurs in many igneous rocks (granites, basalts, etc.), in minute hexagonal non-pleochroic needles, giving faint polarization tints; also in large crystals and massive beds associated with metamorphic rocks.

Vivianite (Blue iron-earth, $Fe_3P_2O_8$, $8H_2O$) occurs crystallized in metalliferous veins; the earthy variety is not infrequent in peat-mosses where animal matter has decayed, and is sometimes to be observed coating fossil fishes as a fine layer like the bloom of a plum.

9. FLUORIDES. The element fluorine, though widely diffused in nature, occurs as an important constituent of comparatively few minerals. Its most abundant compound is with Calcium as the common mineral Fluorite. It occurs also with sodium and aluminium in the mineral Cryolite.

Fluorite (Fluor-spar, CaF_2) occurs generally in veins, especially in association with metallic ores.

10. CHLORIDES. There is only one chloride of importance as a constituent of rocks—sodium-chloride or common salt ($NaCl$), which, occurring chiefly in beds, is described among the rocks at p. 259. Carnallite ($KClMgCl_26H_2O$), a hydrated chloride of potassium and magnesium, occurs in beds associated with rock-salt, gypsum, etc., in some salt districts (p. 260).

11. SULPHIDES. Sulphur is found united with metals in the form of sulphides, many of which form common minerals. The sulphides of lead, silver, copper, zinc, antimony, etc., are of great commercial importance. Iron-disulphide, however, is the only one which merits consideration here as a rock-forming substance. It is formed at the present day by some thermal springs, and has been developed in many rocks as a result of the action of infiltrating water in presence of decomposing organic matter and iron salts. It occurs in two forms, Pyrite and Marcasite.

Pyrite (Eisenkies, Schwefelkies, FeS_2) occurs disseminated through almost all kinds of rocks, often in great abundance, as among diabases and clay-slates; also frequent in veins or in beds. In microscopic sections of rocks, pyrite appears in small cubical, perfectly opaque crystals, which with reflected light show the characteristic brassy lustre of the mineral, and cannot thus be mistaken for the isometric magnetite, of which the square sections exhibit a characteristic blue-black color. Pyrite when free from marcasite yields but slowly to weathering. Hence its cubical crystals may be seen projecting still fresh from slates which have been exposed to the atmosphere for several generations.[33]

Marcasite (Hepatic pyrites) occurs abundantly among sedimentary formations, sometimes abundantly diffused in minute particles which impart a blue-gray tint, and speedily

[33] For an elaborate paper on the decomposition of Pyrites, see A. A. Julien, Annals New York Acad. Sci. vols. iii. and iv.

weather yellow on exposure and oxidation; sometimes segregated in layers, or replacing the substance of fossil plants or animals; also in veins through crystalline rocks. This form of the sulphide is especially characteristic of stratified fossiliferous rocks, and more particularly of those of Secondary and Tertiary date. It is extremely liable to decomposition. Hence exposure for even a short time to the air causes it to become brown; free sulphuric acid is produced, which attacks the surrounding minerals, sometimes at once forming sulphates, at other times decomposing aluminous silicates and dissolving them in considerable quantity. Dr. Sullivan mentions that the water annually pumped from one mine in Ireland carried up to the surface more than a hundred tons of dissolved silicate of alumina.[34] Iron disulphide is thus an important agent in effecting the internal decomposition of rocks. It also plays a large part as a petrifying medium, replacing the organic matter of plants and animals, and leaving casts of their forms, often with bright metallic lustre. Such casts when exposed to the air decompose.

Pyrrhotine (Magnetic pyrites, Fe_7S_8) is much less abundant than either of the forms of ordinary iron-pyrites, from which it is distinguished by its inferior hardness and its magnetic character.

It will be observed that great differences exist in the relative importance of the minerals above enumerated as constituents of rocks. Prof. Rosenbusch points out that they may be naturally arranged in four groups—1st, ores and accessory ingredients (magnetite, hæmatite, ilmenite, apatite, zircon, spinel, titanite), 2d, magnesian and ferruginous silicates (biotite, amphibole, pyroxene, olivine), 3d, felspathic constituents (felspar proper, nepheline, leucite, melilite, sodalite, hauyne), 4th, free silica.[35]

§ iii. Determination of Rocks

Rocks considered as mineral substances are distinguished from each other by certain external characters, such as the

[34] Jukes' "Manual of Geology," p. 65.

[35] Neues Jahrb. 1882 (ii.) p. 5.

size, form, and arrangement of their component particles. These characters, readily perceptible to the naked eye, and in the great majority of cases observable in hand specimens, are termed *megascopic* or *macroscopic* (pp. 146–156), to distinguish them from the more minute features which, being only visible or satisfactorily observable when greatly magnified, are known as *microscopic* (pp. 161–172). The larger (geotectonic) aspects of rock-structure, which can only be properly examined in the field and belong to the general architecture of the earth's crust, are treated of in Book IV.[36]

In the discrimination of rocks, it is not enough to specify their component minerals, for the same minerals may constitute very distinct varieties of rock. For example, quartz and mica form the massive crystalline rock, greisen, the foliated crystalline rock, mica-schist, and the sedimentary rock, micaceous sandstone. Chalk, encrinal limestone, stalagmite, statuary marble are all composed of calcite. It is needful to take note of the megascopic and microscopic structure and texture, the state of aggregation, color, and other characters of the several masses.

Four methods of procedure are available in the investigation and determination of rocks: 1st, megascopic (macroscopic) examination, either by the rough and ready, but often sufficient, appliances for use in the field, or by those for more careful work indoors; 2d, chemical analysis; 3d, chemical synthesis; 4th, microscopic investigation.

i. *Megascopic (Macroscopic) Examination*

Tests in the field.—The instruments indispensable for the

[36] The student who would pursue physical geology by original research in the field and abroad may consult Boué, "Guide du Géologue Voyageur," 2 vols. 1835; Élie de Beaumont, "Leçons de Géologie pratique," vol. i. 1845; Penning and Jukes-Brown, "Field Geology," 2d edit. 1880; A. Geikie, "Outlines of Field Geology," 4th. edit. 1891. F. v. Richthofen, "Führer für Forschungsreisende," 1886; Grenville Cole, "Aids in Practical Geology," 1891.

investigation of rocks in the field are few in number, and simple in character and application. The observer will be sufficiently accoutred if he carries with him a hammer of such form and weight as will enable him to break off clean, sharp, unweathered chips from the edges of rock-masses, a small lens, a pocket-knife of hard steel for determining the hardness of rocks and minerals, a magnet or a magnetized knife-blade, and a small pocket-phial of dilute hydrochloric acid, or better still some citric acid in powder.

Should the object be to form a collection of rocks, a hammer of at least three or four pounds in weight should be carried: also one or two chisels and a small trimming hammer, weighing about ¼ lb., for reducing the specimens to shape. A convenient size of specimen is 4×3×1 inches. They should be as nearly as possible uniform in size, so as to be capable of orderly arrangement in the drawers or shelves of a case or cabinet. Attention should be paid not only to obtain a thoroughly fresh fracture of a rock, but also a weathered surface, wherever there is anything characteristic in the weathering. Every specimen should have affixed to it a label, indicating as exactly as possible the locality from which it was taken. This information ought always to be written down in the field at the time of collecting, and should be affixed to or wrapped up with the specimen, before it is consigned to the collecting bag. If, however, the student does not purpose to form a collection, but merely to obtain such chips as will enable him to judge of the characters of rocks, a hammer weighing from 1½ to 2 lbs., with a square face and tapering to a chisel edge at the opposite end, will be most useful. The advantage of this form is that the hammer can be used not only for breaking hard stones, but also for splitting open shales and other fissile rocks, so that it unites the uses of hammer and chisel.

It is, of course, desirable that the learner should first acquire some knowledge of the nomenclature of rocks, by carefully studying a collection of correctly named and judiciously selected rock-specimens. Such collections may now be purchased at small cost from mineral dealers, or may be studied in the museums of most towns. Having accustomed his eye to the ordinary external characters of rocks, and become familiar with their names, the student may proceed to determine them for himself in the field.

Finding himself face to face with a rock-mass, and after noting its geotectonic characters (Book IV.), the observer will proceed to examine the exposed or weathered surface.

The earliest lesson he has to learn, and that of which perhaps he will in after life meet with the most varied illustrations, is the extent to which weathering conceals the true aspect of rocks. From what has been said in previous pages, the nature of some of the alterations will be understood, and further information regarding the chemical processes at work will be found in Book III. The practical study of rocks in the field soon discloses the fact, that while, in some cases, the weathered crust so completely obscures the essential character of a rock that its true nature might not be suspected, in other instances, it is the weathered crust that best reveals the real structure of the mass. Spheroidal crusts of a decomposing yellow ferruginous earthy substance, for example, would hardly be identified as a compact dark basalt, yet, on penetrating within these crusts, a central core of still undecomposed basalt may not infrequently be discovered. Again, a block of limestone when broken open may present only a uniformly crystalline structure, yet if the weathered surface be examined it may show many projecting fragments of shells, polyzoa, corals, crinoids, or other organisms. The really fossiliferous nature of an apparently unfossiliferous rock may thus be revealed by weathering. Many limestones also might, from their fresh fracture, be set down as tolerably pure carbonate of lime; but from the thick crust of yellow ochre on their weathered faces are seen to be highly ferruginous. Among crystalline rocks, the weathered surface commonly throws light upon the mineral constitution of the mass, for some minerals decompose more rapidly than others, which are thus left isolated and more easily recognizable. In this manner, the existence of quartz in many felspathic rocks may be detected. Its minute blebs or crystals, which to the naked eye or lens are lost among the brilliant facets of the felspars, stand out amid the dull clay into which these minerals are decomposed.

The depth to which weathering extends should be noted. The student must not be too confident that he has reached its limit, even when he comes to the solid, more or less hard, splintery, and apparently fresh stone. Granite sometimes decomposes into kaolin and sand to a depth of twenty or thirty feet or more. Limestones, on the other hand, have often a mere film of crust, because their substance is almost entirely dissolved and removed by rain (Book III. Part II. Section ii. § 2).

With some practice, the inspection of a weathered surface will frequently suffice to determine the true nature and name of a rock. Should this preliminary examination, and a comparison of weathered and unweathered surfaces, fail to afford the information sought, we proceed to apply some of the simple and useful tests available for field-work. The lens will usually enable us to decide whether the rock is compact and apparently structureless, or crystalline, or fragmental. Having settled this point, we proceed to ascertain the hardness and color of streak, by scratching a fresh surface of the stone. A drop of acid placed upon the scratched surface or on the powder of the streak may reveal the presence of some carbonate. By practice, considerable facility can be acquired in approximately estimating the specific gravity of rocks merely by the hand. The following table may be of assistance, but it must be understood at the outset that a knowledge of rocks can never be gained from instructions given in books, but must be acquired by actual handling and study of the rocks themselves.

i. A fresh fracture shows the rock to be close-grained, dull, with no distinct structure.[37]

α. H. 0·5 or less up to 1. Soft, crumbling or easily scratched with the knife, if not with the finger-nail; emits an earthy smell when breathed upon, does not effervesce with acid; is dark gray, brown, or blue, perhaps red, yellow, or even white=probably some clay rock, such as mudstone, massive shale, or fire-clay (p. 234); or a decomposed felspar-rock, like a close-grained felsite or orthoclase porphyry. If the rock is hard and fissile it may be shale or clay-slate (p. 235).

β. H. 1·5–2. Occurs in beds or veins (perhaps fibrous), white, yellow, or reddish. Sp. gr. 2·2–2·4. Does not effervesce=probably gypsum (pp. 143, 265).

γ. Friable, crumbling, soils the fingers, white, or yellowish, brisk effervescence=chalk, marl, or some pulverulent form of limestone (pp. 244, 260).

δ. H. 3–4. Sp. gr. 2·5–2·7. Pale to dark green or reddish, or with blotched and clouded mixtures of these colors. Streak white; feels soapy; no effervescence,

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[37] In this table, H. = hardness; Sp. gr. = specific gravity. The scale of hardness usually employed is 1, Talc; 2, Rock-salt or gypsum; 3, Calcite; 4, Fluorite; 5, Apatite; 6, Orthoclase; 7, Quartz; 8, Topaz; 9, Corundum; 10, Diamond.

splintery to subconchoidal fracture, edges subtranslucent. See serpentine (p. 301).

ε. H. averaging 3. Sp. gr. 2·6–2·8. White, but more frequently bluish-gray, also yellow, brown and black; streak white; gives brisk effervescence= some form of limestone (pp. 244, 260).

ζ. H. 3·5–4·5. Sp. gr. 2·8–2·95. Yellowish, white, or pale brown. Powder slowly soluble in acid with feeble effervescence, which becomes brisker when the acid is heated with the powder of the stone. See dolomite (pp. 143, 264).

η. H. 3–4. Sp. gr. 3–3·9. Dark brown to dull black, streak yellow to brown, feebly soluble in acid, which becomes yellow; occurs in nodules or beds, usually with shale; weathers with brown or blood-red crust =brown iron-ore. See clay-ironstone (pp. 256, 267); and limonite (pp. 128, 266); if the rock is reddish and gives a cherry-red streak, see hæmatite (pp. 128, 266).

θ. Sp. gr. 2·55. White, gray, yellowish, or bluish, rings under the hammer, splits into thin plates, does not effervesce, weathered crust white and distinct=perhaps some compact variety of phonolite (p. 289. See also felsite, p. 280, and porphyrite, p. 292).

ι. Sp. gr. 2·9–3·2. Black or dark green, weathered crust yellow or brown=probably some close-grained variety of basalt (p. 296), andesite (p. 289), aphanite (p. 288), or amphibolite (p. 314).

κ. H. 6–6·5, but less according to decomposition. Sp. gr. 2·55–2·7. Can with difficulty be scratched with the knife when fresh. White, bluish-gray, yellow, lilac, brown, red; white streak; sometimes with well defined white weathered crust, no effervescence= probably a felsitic rock (p. 280).

λ. H. 7. Sp. gr. 2·5–2·9. The knife leaves a metallic streak of steel upon the resisting surface. The rock is white, reddish, yellowish, to brown or black, very finely granular or of a horny texture, gives no reaction with acid=probably silica in the form of jasper, hornstone, flint, chalcedony, hälleflinta (pp. 127, 316), adinole (p. 317).

II. A fresh fracture shows the rock to be glassy.

Leaving out of account some glass-like but crystalline minerals, such as quartz and rock-salt, the number of vitreous rocks is comparatively small. The true nature of the mass in question will probably not be difficult to determine.

It must be one of the Massive volcanic rocks (p. 269 *et seq.*). If it occurs in association with siliceous lavas (liparites, trachytes) it will probably be obsidian (p. 282), or pitchstone (p. 283); if it passes into one of the basalt-rocks, as so commonly happens along the edges of dikes and intrusive sheets, it is a glassy form of basalt (p. 297). Each of the three great series of eruptive rocks, Acid, Intermediate, and Basic, has its glassy varieties (see pp. 282–284, 297).

iii. A fresh fracture shows the rock to be crystalline.

If the component crystals are sufficiently large for determination in the field, they may suggest the name of the rock. Where, however, they are too minute for identification even with a good lens, the observer may require to submit the rock to more precise investigation at home, before its true character can be ascertained. For the purposes of field-work, however, the following points should be noted.

α. The rock can be easily scratched with the knife.

(*a*) Effervesces briskly with acid = limestone. (*b*) Powder of streak effervesces in hot acid. See dolomite (p. 264). (*c*) No effervescence with acid: may be granular crystalline gypsum (alabaster) or anhydrite (pp. 143, 265).

β. The rock is not easily scratched. It is almost certainly a silicate. Its character should be sought among the massive crystalline rocks (p. 268). If it be heavy, appear to be composed of only one mineral, and have a marked greenish tint, it may be some kind of amphibolite (p. 314); if it consist of some white mineral (felspar) and a green mineral which gives it a distinct green color, while the weathered crust shows more or less distinct effervescence, it may be a fine-grained diorite (p. 286), or diabase (p. 296); if it be gray and granular, with striated felspars and dark crystals (augite and magnetite), with a yellowish or brownish weathered crust, it is probably a dolerite (p. 294) or andesite (p. 289); if it be compact, finely-crystalline, scratched with difficulty, showing crystals of orthoclase, and with a bleached argillaceous weathered crust, it is probably an orthoclase-porphyry (p. 285), or quartz-porphyry (p. 278). The occurrence of distinct blebs or crystals of quartz in the fresh fracture or weathered face will suggest a place for the rock in the quartziferous crystalline series (granites, quartz-porphyries, rhyolites), or among the gneisses and schists.

iv. A fresh fracture shows the rock to have a foliated structure.

The foliated rocks are for the most part easily recognizable by the prominence of their component minerals (p. 303). Where the minerals are so intimately mingled as not to be separable by the use of the lens, the following hints may be of service:

α. The rock has an unctuous feel, and is easily scratched. It may be talc-schist (p. 315), chlorite-schist (p. 315), sericitic mica-schist (p. 319), or foliated serpentine (p. 316).

β. The rock emits an earthy smell when breathed on, is harder than those included in *α*, is fine-grained, dark-gray in color, splits with a slaty fracture and contains perhaps scattered crystals of iron-pyrites or some other mineral. It is some argillaceous-schist or clay-slate, the varieties of which are named from the predominant inclosed mineral, as chiastolite-slate, andalusite-schist, ottrelite-schist, etc. (p. 309); if it has a silky lustre it may be phyllite.

γ. The rock is composed of a mass of ray-like or fibrous crystals matted together. If the fibres are exceedingly fine, silky, and easily separable, it is probably asbestos; if they are coarser, greenish to white, glassy, and hard, it is probably an actinolite-schist (p. 314). Many serpentines are seamed with veins of the fine silky fibrous variety termed chrysotile, which is easily scratched.

δ. The rock has a hardness of nearly 7, and splits with some difficulty along micaceous folia. It is probably a quartzose variety of mica-schist, quartz-schist, or gneiss (pp. 309, 317–319).

ε. The rock shows on its weathered surface small particles of quartz and folia of mica in a fine decomposing base. It is probably a fine-grained variety of mica-schist or gneiss.

v. A fresh fracture shows the rock to have a fragmental (clastic) structure.

Where the component fragments are large enough to be seen by the naked eye or with a lens, there is usually little difficulty in determining the true nature and proper name of the rock. Two characters require to be specially considered—the component fragments and the cementing paste.

1. *The Fragments.*—According to the shape, size, and composition of the fragments, different names are assigned to clastic rocks.

α. Shape.—If the fragments are chiefly rounded, the rock may be sought in the sand and gravel series (p. 224), while if they are large and angular, it may be classed as a breccia (p. 230). Some mineral substances, however, do not acquire rounded outlines, even after long-continued attrition. Mica, for example, splits up into thin laminæ, which may be broken into small flakes or spangles, but never become rounded granules. Other minerals, also, which have a ready cleavage, are apt to break up along their cleavage-planes, and thus to retain angular contours. Calc-spar is a familiar example of this tendency. Organic remains composed of this mineral (such as crinoids and echinoids) may often be noticed in a very fragmentary condition, having evidently been subjected to long-continued comminution. Yet angular outlines and fresh or little worn cleavage-surfaces may be found among them. Many limestones consist largely of sub-angular organic débris. Angular inorganic detritus is characteristic of volcanic breccias and tuffs (p. 238).

β. Size.—Where the fragments are hard, rounded, or sub-angular quartzose grains, the size of a pin's head or less, the rock is probably some form of sandstone (p. 231). Where they range up to the size of a pea, it may be a pebbly sandstone, fine conglomerate or grit; where they vary from the size of a pea to that of a walnut, it is an ordinary gravel or conglomerate; where they range up to the size of a man's head or larger, it is a coarse shingle or conglomerate. A considerable admixture of sub-angular stones makes it a brecciated conglomerate or breccia; but where the materials are loosely aggregated, the deposit may be some kind of glacial drift, such as moraine-stuff or bowlder-clay (p. 235). Large angular and irregular blocks are characteristic of coarse volcanic agglomerates (p. 240).

γ. Composition.—In the majority of cases, the fragments are of quartz, or at least of some siliceous and enduring mineral. Sandstones consist chiefly of rounded quartz-grains (p. 231). Where these are unmixed with other ingredients, the rock is sometimes distinguished as a quartzose sandstone. Such a rock when indurated becomes quartzite (p. 311). Among the quartz-grains, minute fragments of other minerals may be observed. When any one of these is prominent, it may give a name to the variety of sandstone, as felspathic, micaceous (p. 186). Volcanic tuffs and breccias are characterized by the occurrence of lapilli (very commonly *cellular*) of the lavas from the explosion of which they have been formed. Among interbedded volcanic rocks, the student will meet with some which he may be at a loss whether to class as volcanic, or as formed of ordinary sediment. They consist of an intermixture of volcanic detritus with sand or mud, and pass on the one side into true tuffs, on the other into sandstones, shales, limestones, etc. If the component fragments of a non-crystalline rock give a brisk effervescence with acid, they are calcareous, and the rock (most likely a limestone, or at least of calcareous composition) may be searched for traces of fossils.

2. *The Paste.*—It sometimes happens that the component fragments of a clastic rock cohere merely from pressure and without any discoverable matrix. This is occasionally the case with sandstone. Most commonly, however, there is some cementing paste. If a drop of weak acid produces effervescence from between the component non-calcareous grains of a rock, the paste is calcareous. If the grains are coated with a red crust which, on being bruised between white paper, gives a cherry-red powder, the cementing material is the anhydrous peroxide of iron. A dark brown or black matrix which can be dissipated by heating is bituminous. Where the component grains are so firmly cemented in an exceedingly hard matrix that they break across rather than separate from each other when the stone is fractured, the paste is probably siliceous.

Determination of Specific Gravity.—The student will find this character of considerable advantage in enabling him to discriminate between rocks. He may acquire some dexterity in estimating, even with the hand, the probable specific gravity of substances; but he should begin by determining it with a balance. Jolly's spring balance is a simple and serviceable instrument for this purpose. It consists of an upright stem having a graduated strip of mirror let into it, in front of which hangs a long spiral wire, with rests at the bottom for weighing a substance in air and in water. For most purposes it is sufficiently accurate, and a determination can be made with it in the course of a few minutes.[38] Another and more convenient instrument has been invented by W. N. Walker, consisting of a lever graduated into inches and tenths, and resting on a knife-edge stand, on one side of which is placed a movable weight, while on the long

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[38] Jolly's spring balance can be obtained through any optician or mineral dealer from Berberich, of Munich, for nine florins or 27s. In the United States it is manufactured by Geo. Wade & Co., at the Hoboken Institute.

graduated side the substance to be weighed is suspended. This instrument has the advantage of not being so liable to get out of order as other contrivances.[39]

Mechanical Analysis.—Much may be learned regarding the composition of a rock by reducing it to powder. In the case of many sandstones and clays this reduction may easily be effected by drying the stone and crumbling it between the fingers. But where the material is too compact for such treatment some fragments of it placed within folds of paper upon a surface of steel may be reduced to powder by a few smart blows of a hammer. The powder can be sifted through sieves of varying degrees of fineness and the separate fragments may be picked out with a fine brush and examined with a lens. If they are dark in color they may be placed on white paper, if light-colored they are more readily observed upon a black paper. Portions of this powder may be carefully washed and mounted with Canada balsam on glass, as in the way described below for microscopic slices. In this way the constituent minerals of many crystalline rocks may be isolated and studied with great facility. For purposes of comparison specimens of the rock-forming minerals should be procured and treated in a similar way. A series of typical preparations of the powder or minute fragments of such minerals affords to the student an admirable basis from which to start in his study of the crystallographic and optical characters of the minerals which he will require to identify among the constituents of rocks.

Another method of isolating the several components of certain rocks is by washing the triturated materials in water and allowing the sediment to subside. The finer and lighter particles may be drawn off, while the coarser and heavier grains will sink according to their respective specific gravities, and may then be separated and collected. This may be done by means of a wide tube with a stop-cock at the bottom, or by gently washing the powder with water on an inclined surface, when, as in the analogous treatment of veinstones and ores in mining, the particles arrange themselves according to their respective gravities, the lightest being swept away by the current.

Magnetic particles may be extracted with a magnet, the end of which is preserved from contact with the powder by

[39] See Geol. Mag. 1883, p. 109, for a description and drawing of this instrument, and the manner of using it. It may be obtained of Lowden, optician, Dundee, and How & Co., Farringdon Street, London. Its price is 31s. 6d.

being covered with fine tissue-paper. An electro-magnet will at once withdraw the particles of minerals which contain far too little iron to be ordinarily recognized as magnetic; in this way the particles of a ferruginous magnesian mica may in a few seconds be gathered out of the powder of a granite.[40]

Where the difference between the specific gravity of the component minerals of a rock is slight, they may be separated by means of a solution of given density. Mr. E. Sonstadt proposed the use of a saturated solution of iodide of mercury in iodide of potassium, which has a maximum density of nearly 3·2.[41] Rohrbach's solution, consisting of iodide of mercury and iodide of barium, has a density of as much as 3·588.[42] More serviceable is the solution of borotungstate of cadium, with a density of 3·28, proposed by D. Klein.[43] The powder of a rock being introduced into one of these liquids, those particles whose specific gravity exceeds that of the liquid will sink to the bottom, while those which are lighter will float. This process allows of the separation of the felspars from each other, and at once eliminates the heavy minerals such as hornblende, augite, and black mica. By the addition of water or other liquid, as the case may be, the specific gravity may be reduced, and different solutions of given density may be employed for determining and isolating rock-constituents. This method of analysis is important in affording a ready means of separating the quartz and felspar of a rock.[44]

Hydrofluoric acid may be used in separating the mineral constituents of rocks. The rock to be studied is reduced to powder and introduced gently into a platinum capsule containing the concentrated acid. During the consequent effervescence, the mixture is cautiously stirred with a platinum spatula. Some minerals are converted into fluorides, others into fluosilicates, while some, particularly the iron-

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[40] Mém. Acad. des Sci. xxxii. No. 11; Fouqué and Michel-Lévy, "Minéralogie Micrographique," p. 115.

[41] Chem. News, xxix. (1874), p. 128.

[42] Neues Jahrb. 1883, p. 186.

[43] Compt. rend. xciii. (1881), p. 318. More recently R. Brauns has introduced methylene iodide, which gives a density of 3·33 and is diluted with benzole. Neues Jahrb. 1886, ii. p. 72. See also J. W. Retgers, op. cit. 1889, ii. p. 185.

[44] Fouqué and Michel-Lévy, "Minéralogie Micrographique," p. 171. Thoulet, Bull. Soc. Min. France, ii. (1879), p. 17. A cheap form of instrument for isolating minerals by means of heavy solutions is described by Mr. J. W. Evans, Geol. Mag. 1891, p. 67.

magnesia species, remain undissolved. The thick jelly of silica and alumina is removed with water, and the crystalline minerals lying at the bottom can then be dried and examined. By arresting the solution at different stages the different minerals may be isolated. This process is admirably adapted for collecting the pyroxene of pyroxenic rocks.[45]

ii. *Chemical Analysis*

The determination of the chemical composition of rocks by detailed analysis in the wet way, demands an acquaintance with practical chemistry which comparatively few geologists possess, and is consequently for the most part left in the hands of chemists, who are not geologists. But as some theoretical questions in geology involve a considerable knowledge of chemical processes, so a satisfactory analysis of rocks is best performed by one who understands the nature of the geological problems on which such an analysis may be expected to throw light. As a rule, detailed chemical analysis lies out of the sphere of a geologist's work: yet the wider his knowledge of chemical laws and methods the better. He should at least be able to employ with accuracy the simpler processes of chemical research.

Treatment with Acid.—The geologist's accoutrements for the field should include a small bottle of powdered citric acid, or one with a mineral acid, and provided with a glass stopper prolonged downward into a point. Dilute hydrochloric acid has been commonly employed; but H. C. Bolton proposed in 1877 the use of organic acids in place of the usual mineral acids. Citric acid is particularly serviceable for the purpose, and has the advantage over the mineral acids that it can be carried in powder, and a strong solution of it in water can be made in such quantity and at such time as may be required. A little of the powder placed with the point of a knife on a surface of limestone and moistened with a drop of water will give the proper reaction.[46]

When a drop of acid gives effervescence upon a surface of rock, the reaction is caused by the liberation of bubbles

[45] Fouqué and Michel-Lévy, op. cit. p. 116.

[46] Ann. New York Acad. Sci. i. (1879) p. 1. Chem. News, xxxvi. xxxvii., xxxviii., xliii.

of carbon dioxide, as this oxide is replaced by the more powerful acid. Hence effervescence is an indication of the presence of carbonates, and when brisk is specially characteristic of calcium-carbonate. Limestone and markedly calcareous rocks may thus at once be detected. By the same means, the decomposition of such rocks as dolerite may be traced to a considerable distance inward from the surface, the original lime-bearing silicate of the rock having been decomposed by infiltrating rain-water, and partially converted into carbonate of lime. This carbonate being far more sensitive to the acid-test than the other carbonates usually to be met with among rocks, a drop of weak cold acid suffices to produce abundant effervescence even from a crystalline face. But the effervescence becomes much more marked if we apply the acid to the powder of the stone. For this purpose, a scratch may be made and then touched with acid, when a more or less copious discharge of carbonic acid may be obtained, where otherwise it might appear so feebly as perhaps even to escape observation. Some carbonates, dolomite for example, are hardly affected by acid until it is heated. This is done by placing some fragments of the substance at the bottom of a test-tube, covering them with acid and applying a flame.

It is a convenient method of roughly estimating the purity of a limestone, to place a fragment of the rock in acid. If there is much impurity (clay, sand, oxide of iron, etc.), this will remain behind as an insoluble residue, and may then be further tested chemically, or examined with the microscope. In this way many limestones among the crystalline schists may be dissolved in acetic acid, leaving a residue of pyroxenes, amphiboles, micas or other silicates. Of course the acid, especially if strong mineral acid is employed, may attack some of the non-calcareous constituents, so that it cannot be concluded that the residue absolutely represents everything present in the rock except the carbonate of lime; but the proportion of non-calcareous matter so dissolved by the acid will usually be small.

Further chemical processes.—A thorough chemical analysis of a rock or mineral is indispensable for the elucidation of its composition. But there are several processes by which, until that complete analysis has been made, the geologist may add to his knowledge of the chemical nature of the objects of his study. It is commonly the case that minerals about which he may be doubtful are precisely those which, from their small size, are most difficult of separation from the rest of the rock preparatory to analytical processes. The mineral apatite, for example, occurs in minute hexagonal prisms, which on cross-fracture might be mistaken for nepheline, or even sometimes for quartz. If, however, a drop of nitric acid solution of molybdate of ammonia be placed upon one of these crystals, a yellow precipitate will appear if it be apatite. Nepheline, which is another hexagonal mineral likewise abundant in some rocks, gives no yellow precipitate with the ammonia solution, while if a drop of hydrochloric acid be put over it, crystals of chloride of sodium or common salt will be obtained. These reactions can be observed even with minute crystals or fragments, by placing them on a glass slide under the microscope and using an exceedingly attenuated pipette for dropping the liquid on the slide.[47]

Two ingenious applications of chemical processes to the determination of minute fragments of minerals are now in use. In one of these, devised by Boricky,[48] hydrofluosilicic acid of extreme purity is employed. This acid decomposes most silicates, and forms from their bases hydrofluosilicates. A particle about the size of a pin's head of the mineral to be examined is fixed by its base upon a thin layer of Canada balsam spread upon a slip of glass, and a drop of the acid is placed upon it. The preparation is then set in moist air near a saucer of water under a bell-glass for twenty-four hours, after which it is inclosed in dry air, with chloride of calcium. In a few hours the hydrofluosilicates crystallize out upon the balsam and can be examined with the microscope. Those of potassium take the form of cubes, of sodium hexagonal prisms, etc.

The second process, devised by Szabo, consists in utilizing the colorations given to the flame of a Bunsen-burner by sodium and potassium. An elongated splinter of the mineral to be examined is first placed in the outer or oxidizing part of the flame near the base, and then in the re-

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[47] An excellent treatise on the chemical examination of minerals under the microscope is that by MM. Klement and Renard, "Réactions microchemiques à cristaux et leur application en analyse qualitative," Brussels, 1886. See also H. Behrens, Ann. École Polytechnique de Delft, i. 1885, p. 176; Neues Jahrb. vii. Beilage Band. p. 435; Zeitsch. f. Analyt. Chemie, xxx. ii. p. 126–174 (1891).

[48] Archiv Naturwiss. Landesdurchforschung von Böhmen, iii. fasc. 3, 1876. "Elemente einer neuen chemisch-mikroskopischen Mineral- und Gesteinsanalyse." Prag. 1877.

ducing part further up and nearer the centre. The amount of sodium present in the mineral is indicated by the extent to which the flame is colored yellow. The potassium is similarly estimated, but the flame is then looked at with cobalt glass, so as to eliminate the influence of the sodium.[49]

Blow-pipe Tests.—The chemical tests with the blow-pipe are simple, easily applied, and require only patience and practice to give great assistance in the determination of minerals. If unacquainted with blow-pipe analysis, the student must refer to one or other of the numerous text-books on the subject, some of which are mentioned below.[50] For early practice the following apparatus will be found sufficient:

1. Blow-pipe.
2. Thick-wicked candle, or a tin box filled with the material of Child's night-lights, and furnished with a piece of Freyberg wick in a metallic support.
3. Platinum-tipped forceps.
4. A few pieces of platinum wire in lengths of three or four inches.
5. A few pieces of platinum foil.
6. Some pieces of charcoal.
7. A number of closed and open tubes of hard glass.
8. Three small stoppered bottles containing sodium-carbonate, borax, and microcosmic salt.
9. Magnet.

This list can be increased as experience is gained. The whole apparatus may easily be packed into a box which will go into the corner of a portmanteau.

iii. *Chemical Synthesis*

As already remarked (p. 118), much interesting light has been thrown on the natural conditions in which minerals

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[49] Szabo, "Ueber eine neue Methode die Felspathe auch in Gesteinen zu bestimmen." Buda-Pesth, 1876.

[50] The great work on the blow-pipe is Plattner's, of which an English translation has been published. Elderhorst's "Manual of Qualitative Blow-pipe Analysis and Determinative Mineralogy," by H. B. Nason and C. F. Chandler (Philadelphia: N. S. Porter and Coates), is a smaller but useful volume; while still less pretending is Scheerer's "Introduction to the Use of the Mouth Blow-pipe," of which a third edition by H. F. Blandford was published in 1875 by F. Norgate. An admirable work of reference will be found in Prof. Brush's "Manual of Determinative Mineralogy" (New York: J. Wiley and Son). F. v. Kobell's "Tafeln zur Bestimmung der Mineralien" (Munich) are useful. A valuable summary will be found in Prof. Cole's "Aids in Practical Geology," 1891.

and rocks have been formed, by actual experiments in which these bodies are reproduced artificially. Since the classic experiments of Hall much progress has been made in this subject, notably from the prolonged and admirable researches carried on in Paris by Prof. Daubrée and by Messrs. Fouqué and Michel-Lévy. To some of the results obtained by these observers reference will be made in Book III. Part I. Sect. iv. The processes of investigation have been grouped in three classes. 1st. Those by the "dry way" as in fusion and sublimation, sometimes simply, sometimes with the intervention of a mineralizing agent such as borax, borates, fluorides, chlorides, etc. 2d. Those by the "wet way" where water or steam are used as dissolvents either by themselves or with the aid of some mineralizing agent; and 3d, Those where some combination of the two foregoing methods is employed, that is, where water or steam is made to act at a high temperature and under great pressure.[51]

iv. *Microscopic Investigation*[52]

The value of the microscope as an aid in geological research is now everywhere acknowledged. Some information may here be given as to the methods of procedure in microscopical inquiry.

1. **Preparation of microscopic slides of rocks and minerals.**—The observer ought to be able to prepare his own slices, and in many cases will find it of advantage to do so, or at least personally to superintend their preparation by others. It is desirable that he should know at the outset that no costly or unwieldy set of apparatus is needful for his purpose. If he is resident in one place and can accommodate a cutting machine such as a lapidary's lathe, he will find the process

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[51] See on this subject Daubrée's great work "Géologie Expérimentale," 1879; Fouqué et Michel-Lévy, "Synthèse des Minéraux et des Roches," 1882; Stanislas Meunier, "Les Méthodes de Synthèse en Minéralogie," 1891; also postea, p. 513 *et seq.*

[52] On the microscopic investigation of rocks consult Fouqué and Michel-Lévy, "Minéralogie Micrographique," 2 vols. Paris, 1879; Michel-Lévy, "Les Minéraux des Roches," Paris, 1888; Michel-Lévy and Lacroix, "Tableaux des Minéraux des Roches," 1889; Rosenbusch, "Mikroskopische Physiographie der Mineralien und Gesteine," 2 vols., one of which has been translated into English by Iddings and published by Macmillan & Co.; also his "Hülfstabellen zur Mikroskopischen Mineralbestimmung," 1888, translated into English by F. H. Hatch and published by Swan Sonnenschein & Co.; F. Rutley, "Rock-forming Minerals," London, 1888, and Prof. Cole's volume above cited.

of preparing rock-slices greatly facilitated.[53] The thickness of each slice must be mainly regulated by the nature of the rock, the rule being to make the slice as thin as can conveniently be cut, so as to save labor in grinding down afterward. Perhaps the thickness of a shilling may be taken as a fair average. The operator, however, may still further reduce this thickness by cutting and polishing a face of the specimen, cementing that on glass in the way to be immediately described, and then cutting as close as possible to the cemented surface. The thin slice thus left on the glass can then be ground down with comparative ease.

Excellent rock-sections, however, may be prepared without any machine, provided the operator possesses ordinary neatness of hand and patience. He must procure as thin chips as possible. Should the rocks be accessible to him in the field, he should select the freshest portions of them, and by a dexterous use of the hammer, break off from a sharp edge a number of thin splinters or chips, out of which he can choose one or more for rock-slices. These chips may be about an inch square. It is well to take several of them, as the first specimen may chance to be spoiled in the preparation. The geologist ought also always to carry off a piece of the same block from which his chip is taken, that he may have a specimen of the rock for future reference and comparison. Every such hand-specimen, as well as the chips belonging to it, ought to be wrapped up in paper on the spot where it is obtained, and with it should be placed a label containing the name of the locality and any notes that may be thought necessary. It can hardly be too frequently reiterated that all such field-notes ought as far as possible to be written down on the ground, when the actual facts are before the eye for examination.

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[53] A machine well adapted for both cutting and polishing was devised some years ago by Mr. J. B. Jordan, and may be had of Messrs. Cotton and Johnson, Gerrard Street, Soho, London, for £10 10s. Another slicing and polishing machine, invented by Mr. F. G. Cuttell, costs £6 10s. These machines are too unwieldy to be carried about the country by a field-geologist. Fuess of Berlin supplies two small and convenient hand-instruments, one for slicing, the other for grinding and polishing. The slicing-machine is not quite so satisfactory for hard rocks as one of the larger, more solid forms of apparatus worked by a treadle. But the grinding-machine is useful, and might be added to a geologist's outfit without material inconvenience. If a lapidary is within reach, much of the more irksome part of the work may be saved by getting him to cut off the thin slices in directions marked for him upon the specimens. Many lapidaries now undertake the whole labor of cutting and mounting microscopic slides.

Having obtained his thin slices, either by having them slit with a machine or by detaching with a hammer as thin splinters as possible, the operator may proceed to the preparation of them for the microscope. For this purpose the following simple apparatus is all that is absolutely needful, though if a grinding-machine be added it will save time and labor.

List of Apparatus required in the Preparation of Thin Slices of Rocks and Minerals for Microscopical Examination

1. A cast-iron plate ¼ inch thick and 9 inches square.
2. Two pieces of plate-glass, 9 inches square.
3. A Water of Ayr stone, 6 inches long by 2¼ inches broad.
4. Coarse emery (1 lb. or so at a time).
5. Fine or flour-emery (ditto).
6. Putty powder (1 oz.).
7. Canada balsam. (There is an excellent kind prepared by Rimmington, Bradford, specially for microscopic preparations, and sold in shilling bottles.)
8. A small forceps, and a common sewing-needle with its head fixed in a cork.
9. Some oblong pieces of common flat window-glass; 2×1 inches is a convenient size.
10. Glasses with ground edges for mounting the slices upon. They may be had at any chemical instrument maker's in different sizes, the commonest in this country being 3×1 inches, though this size is rather too long for convenient handling on a rotating stage.
11. Thin covering-glasses, square or round. These are sold by the ounce; ¼ oz. will be sufficient to begin with.
12. A small bottle of spirits of wine.

The first part of the process consists in rubbing down and polishing one side of the chip or slice, if this has not already been done in cutting off a slice affixed to glass, as above mentioned. We place the chip upon the wheel of the grinding-machine, or, failing that, upon the iron plate, with a little coarse emery and water. If the chip is so shaped that it can be conveniently pressed by the finger against the plate and kept there in regular horizontal movement, we may proceed at once to rub it down. If, however, we find a difficulty, from its small size or otherwise, in holding the chip, one side of it may be fastened to the end of a bobbin or other convenient bit of wood by means of a cement formed of three parts of resin and one of beeswax, which is easily softened by heating. A little practice will show that a slow, equable motion with a certain steady pressure is most effectual in producing the desired flatness of surface. When all the roughnesses have been removed, which can be told after the chip has been dipped in water so as to remove the mud and emery, we place the specimen upon the square of plate-glass, and with flour-emery and water continue to rub it down until all the scratches caused by the coarse emery have been removed and a smooth polished surface has been produced.[54] Care should be taken to wash the chip entirely free of any grains of coarse emery before the polishing on glass is begun. It is desirable also to reserve the glass for polishing only. The emery gets finer and finer the longer it is used, so that by remaining on the plate it may be used many times in succession. Of course the glass itself is worn down, but by using alternately every portion of its surface and on both sides, one plate may be made to last a considerable time. If after drying and examining it carefully, we find the surface of the chip to be polished and free from scratches, we may advance to the next part of the process. But it will often happen that the surface is still finely scratched. In this case we may place the chip upon the Water of Ayr stone and with a little water gently rub it to and fro. It should be held quite flat. The Water of Ayr stone, too, should not be allowed to get worn into a hollow, but should also be kept quite flat, otherwise we shall lose part of the chip. Some soft rocks, however, will not take an unscratched surface even with the Water of Ayr stone. These may be finished with putty powder, applied with a bit of woollen rag.

The desired flatness and polish having been secured, and all trace of scratches and dirt having been completely removed, we proceed to a further stage, which consists in grinding down the opposite side and reducing the chip to the requisite degree of thinness. The first step is now to cement the polished surface of the chip to one of the pieces of common glass. A thin piece of iron (a common shovel

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[54] Exceedingly impalpable emery powder may be obtained by stirring some of the finest emery in water, and after the coarse particles have subsided, pouring off the liquid and allowing the fine suspended dust gradually to subside. Filtered and dried, the residue can be kept for the more delicate parts of the polishing.

does quite well) is heated over a fire, or is placed between two supports over a gas-flame.[55] On this plate must be laid the piece of glass to which the slice is to be affixed, together with the slice itself. A little Canada balsam is dropped on the centre of the glass and allowed to remain until it has acquired the necessary consistency. To test this condition, the point of a knife should be inserted into the balsam, and on being removed should be rapidly cooled by being pressed against some cold surface. If it soon becomes hard enough to resist the pressure of the finger nail, it has been sufficiently heated. Care, however, must be observed not to let it remain too long on the hot plate; for it will then become brittle and start from the glass at some future stage, or at least will break away from the edges of the chip and leave them exposed to the risk of being frayed off. The heat should be kept as moderate as possible, for if it becomes too great it may injure some portions of the rock. Chlorite, for example, is rendered quite opaque if the heat is so great as to drive off its water.

When the balsam is found to be ready, the chip, which has been warmed on the same plate, is lifted with the forceps, and laid gently down upon the balsam. It is well to let one end touch the balsam first, and then gradually to lower the other, as in this way the air is driven out. With the point of a needle or a knife the chip should be moved about a little, so as to expel any bubbles of air and promote a firm cohesion between the glass and the stone. The glass is now removed with the forceps from the plate and put upon the table, and a lead weight or other small heavy object is placed upon the chip, so as to keep it pressed down until the balsam has cooled and hardened. If the operation has been successful, the slide ought to be ready for further treatment as soon as the balsam has become cold. If, however, the balsam is still soft, the glass must be again placed on the plate and gently heated, until on cooling, the balsam fulfils the condition of resisting the pressure of the finger-nail.

Having now produced a firm union of the chip and the glass, we proceed to rub down the remaining side of the stone with coarse emery on the iron plate as before. If the glass cannot be held in the hand or moved by the sim-

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[55] A piece of wire-gauze placed over the flame, with an interval of an inch or more between it and the overlying thin iron plate, tends to diffuse the heat and prevent the balsam from being unequally heated.

ple pressure of the fingers, which usually suffices, it may be fastened to the end of the bobbin with the cement as before. When the chip has been reduced until it is tolerably thin; until, for example, light appears through it when held between the eye and the window, we may, as before, wash it clear of the coarse emery and continue the reduction of it on the glass plate with fine emery. Crystalline rocks, such as granite, gneiss, diorite, dolerite, and modern lavas, can be thus reduced to the required thinness on the glass plate. Softer rocks may require gentle treatment with the Water of Ayr stone.

The last parts of the process are the most delicate of all. We desire to make the section as thin as possible, and for that purpose continue rubbing until after one final attempt we may perhaps find to our dismay that great part of the slice has disappeared. The utmost caution should be used. The slide should be kept as flat as possible, and looked at frequently, that the first indications of disruption may be detected. The thinness desirable or attainable depends in great measure upon the nature of the rock. Transparent minerals need not be so much reduced as more opaque ones. Some minerals, indeed, remain absolutely opaque to the last, like pyrite, magnetite, and ilmenite.

The slide is now ready for the microscope. It ought always to be examined with that instrument at this stage. We can thus see whether it is thin enough, and if any chemical tests are required they can readily be applied to the exposed surface of the slice. If the rock has proved to be very brittle, and we have only succeeded in procuring a thin slice after much labor and several failures, nothing further should be done with the preparation, unless to cover it with glass, as will be immediately explained, which not only protects it, but adds to its transparency. But where the slice is not so fragile, and will bear removal from its original rough scratched piece of glass, it should be transferred to one of the glass-slides (No. 10). For this purpose, the preparation is once more placed on the warm iron plate, and close alongside of it is put one of the pieces of glass which has been carefully cleaned, and on the middle of which a little Canada balsam has been dropped. The heat gradually loosens the cohesion of the slice, which is then very gently pushed with the needle or knife along to the contiguous clean slip of glass. Considerable practice is needed in this part of the work, as the slice, being so thin, is apt to go to pieces in being transferred. A gentle inclination of the warm plate, so that a tendency may be given to the slice to slip downward of itself on to the clean glass, may be advantageously given. We must never attempt to lift the slice. All shifting of its position should be performed with the point of the needle or other sharp instrument. If it goes to pieces we may yet be able to pilot the fragments to their resting-place on the balsam of the new glass, and the resulting slide may be sufficient for the required purpose.

When the slice has been safely conducted to the centre of the glass slip, we put a little Canada balsam over it, and warm it as before. Then taking one of the thin cover-glasses with the forceps, we allow it gradually to rest upon the slice by letting down first one side, and then by degrees the whole. A few gentle circular movements of the cover-glass with the point of the needle or forceps may be needed to insure the total disappearance of air-bubbles. When these do not appear, and when, as before, we find that the balsam has acquired the proper degree of consistence, the slide containing the slice is removed, and placed on the table with a small lead weight above it in the same way as already described. On becoming quite cold and hard the superabundant balsam round the edge of the cover-glass may be scraped off with a knife, and any which still adheres to the glass may be removed with a little spirits of wine. Small labels should be kept ready for affixing to the slides to mark localities and reference numbers. Thus labelled, the slide may be put away for future study and comparison.

The whole process seems perhaps a little tedious. But in reality much of it is so mechanical, that after the mode of manipulation has been learned by a little experience, the rubbing-down may be done while the operator is reading. Thus in the evening, when enjoying a pleasant book after his day in the field, he may at the same time, after some practice, rub down his rock-chips, and thus get over the drudgery of the operation almost unconsciously.

Boxes, with grooved sides or with flat trays for carrying microscopic slides, are sold in different sizes. Such boxes are most convenient for a travelling equipage, as they go into small space, and with the help of a little cotton-wool they hold the glass slides firmly without the risk of breakage. For a final resting-place, a case with shallow trays or drawers in which the slides can lie flat is most convenient.

2. **The Microscope.**—Unless the observer proposes to enter

into great detail in the investigation of the minuter parts of rock-structure, he does not require a large and expensive instrument. For most geological purposes, objectives of 2, 1, and ¼ inch focal length are sufficient. But it is desirable also for special work, such as the investigation of crystallites and inclusions of minerals, to have an objective capable of magnifying up to 200 or 300 diameters. An instrument with fairly good glasses of these powers, according to the arrangement of object-glasses and eye-pieces, may be had of some London makers for £5. But for some of the most important parts of the microscopical study of rocks a rotating stage is requisite, the presence of which necessarily adds to the cost of the instrument. One of the best microscopes specially adapted for petrographical research is that devised by Mr. A. Dick, and manufactured by Swift & Son, of 81 Tottenham Court Road, London, price £18 without objectives.

Among the indispensable adjuncts are two Nicol-prisms, one (polarizer) to be fitted below the stage, the other (analyzer) most advantageously placed over the eye-piece. A quartz-wedge is useful in examination with polarized light. A nose-piece for two objectives, screwed to the foot of the tube, saves time and trouble by enabling the observer at once to pass from a low to a high power. The numerous pieces of apparatus necessary for physiological work are not needed in the examination of rocks and minerals.

3. **Methods of Examination.**—A few hints may be here given for the guidance of the student in making his own microscopic observations, but he must consult some of the special treatises, mentioned on p. 161, for full details.

Reflected Light.—It is not infrequently desirable to observe with the microscope the characters of a rock as an opaque object. This cannot usually be done with a broken fragment of the stone, except of course with very low powers. Hence one of the most useful preliminary examinations of a prepared slice is to place it in the field, and, throwing the mirror out of gear, to converge as strong a light upon it as can be had, short of bright direct sunlight. The observer can then see some way into the rock and observe the relative thicknesses and forms of its constituents. The advantage of this method is particularly noticeable in the case of opaque minerals. The sulphides and iron-oxides so abundant in rocks appear as densely black objects with transmitted light, and show only their external form. But by throwing a strong light upon their surface, we may often discover not only their distinctive colors, but their characteristic internal structure. Titaniferous iron is an admirable example of the advantage of this method. Seen with transmitted light, that mineral appears in black, structureless grains or opaque patches, though frequently bounded by definite lines and angles. But with reflected light, the cleavage and lines of growth of the mineral can then often be clearly seen, and what seemed to be uniform black patches are found in many cases to inclose bright brassy kernels of pyrite. Magnetite also presents a characteristic blue-black color, which distinguishes it from the other iron-oxides.

Transmitted Light.—It is, of course, with the light allowed to pass through prepared slices that most of the microscopic examination of minerals and rocks is performed. A little experience will show the learner that, in viewing objects in this way, he may obtain somewhat different results from two slices of the same rock according to their relative thinness. In the thicker one, a certain mineral or rock, obsidian for example, will appear perhaps brown or almost black, while in the other what is evidently the same substance may be pale yellow, green, brown, or almost colorless. Triclinic felspars seen in polarized light give only a pale milky light when extremely thin, but present bright chromatic bands when somewhat thicker.

Polarized Light.—By meaus of polarized light, an exceedingly delicate method of investigation is made available. We use both the Nicol-prisms. If the object be singly-refracting, such as a piece of glass, or an amorphous body, or a crystal belonging to some substance which crystallizes in the isometric or cubic system (or if it be a tetragonal, hexagonal or rhombohedral crystal, cut perpendicular to its principal axis), the light will reach our eye apparently unaffected by the intervention of the object. The field will remain dark when the axes of the two prisms are at right angles (crossed Nicols), in the same way as if no intervening object were there. Such bodies are *isotropic.*[56] In all other cases, the substance is doubly-refracting and modifies the polarized beam of light. On rotating one of the prisms, we perceive bands or flashes of color, and numerous lines appear which before were invisible. The field no longer remains dark when the two Nicol-prisms are crossed. Such a substance is *anisotropic.*

[56] But the effect of pressure may give weak color-tints in glasses and in cubic crystals.

It is evident, therefore, that we may readily tell by this means whether or not a rock contains any glassy constituent. If it does, then that portion of its mass will become dark when the prisms are crossed, while the crystalline parts which, in the vast majority of cases, do not belong to the cubic system, will remain conspicuous by their brightness. A thin plate of quartz makes this separation of the glassy and crystalline parts of a rock even more satisfactory. It is placed between the Nicol-prisms, which may be so adjusted with reference to it that the field of the microscope appears uniformly violet. The glassy portion of any rock, being singly-refracting or isotropic, placed on the stage will allow the violet light to pass through unchanged, but the crystalline portions, being doubly-refracting or anisotropic, will alter the violet light into other prismatic colors. The object should be rotated in the field, and the eye should be kept steadily fixed upon one portion of the slide at a time, so that any change may be observed. This is an extremely delicate test for the presence of glassy and crystalline constituents.

In searching for the crystallographic system to which a mineral in a microscopic slide should be referred, attention is given to the directions in which the mineral placed between crossed Nicols appears dark, or to what are called the directions of its extinction. It is extinguished (that is, the normal darkness of the field between the crossed Nicols is restored) when two of its axes of elasticity for vibrations of light coincide with the principal sections of the two prisms. During a complete rotation of the slide in the field of the microscope the mineral becomes dark in four positions 90° apart, each of which marks that coincidence. When, on the other hand, the prisms are placed parallel to each other, the coincidence of their principal sections with the axes of elasticity in the mineral allows the maximum of light to pass through, which likewise occurs four times in a complete rotation of the mineral. The different crystallographic systems are distinguishable by the relation between their crystallographic axes and their axes of elasticity. By noting this relation in the case of any given mineral (and there are usually sections enough of each mineral in the same rock-slice to furnish the required data) its crystalline system may be fixed. But in many cases it has been found possible to establish characteristic distinctions for individual mineral species, by noting the angle between the direction of their extinction and certain principal faces.

The determination of whether the component grains of a rock belong to uniaxial or biaxial doubly-refracting minerals is a point of much importance, which is effected by means of an achromatic condenser inserted in the aperture of the stage below the slide and suitably adjusted so as to converge the rays of light within the grain or crystal. The Nicols having been crossed, the eye-piece is removed, and the eye when held a little distance from the open end of the tube will perceive a dark bar, ring, or cross move across the field as the stage is rotated, if the mineral examined has been cut at a favorable angle. By the form and behavior of these indications the uniaxial or biaxial character is made evident.

Pleochroism (*Dichroism*).—Some minerals show a change of color when a Nicol-prism is rotated below them; hornblende, for example, exhibiting a gradation from deep brown to dark yellow. A mineral presenting this change is said to be pleochroic (polychroic, dichroic, trichroic). To ascertain the pleochroism of any mineral we may remove the upper polarizing prism (analyzer) and leave only the lower (polarizer). If as we rotate the latter, no change of tint can be observed, there is no pleochroic mineral present, or at least none which shows pleochroism at the angle at which it has been bisected in the slice. But in a slice of any crystalline rock, crystals may usually be observed which offer a change of hue as the prism goes round. These are examples of pleochroism. This behavior may be used to detect the mineral constituents of rocks. Thus the two minerals hornblende and augite, which in so many respects resemble each other, cannot always be distinguished by cleavage angles, in microscopic slices. But as Tschermak pointed out, augite remains passive or nearly so as the lower prism is rotated: it is not pleochroic, or only very feebly so; while hornblende, on the other hand, especially in its darker varieties, is usually strongly pleochroic. It is to be observed, however, that the same mineral is not always equally pleochroic, and that the absence of this property is therefore less reliable as a negative test, than its presence is as a positive test.

It would be beyond the scope of this volume to enter into the complicated details of the microscopic structure of minerals and rocks. This information must be sought in some of the works specially devoted to it, a few of which are cited on p. 161.

In his examination of rocks with the microscope, the student may find an advantage in propounding to himself the following questions, and referring to the pages here cited.

1st, Is the rock entirely crystalline (pp. 174, 258, 268), consisting solely of crystals of different minerals interlaced; and if so, what are these minerals? 2d, Is there any trace of a glassy ground-mass or base (pp. 178, 204)? Should this be detected, the rock is certainly of volcanic origin (pp. 282, 297). 3d, Can any evidence be found of the devitrification of what may have been at one time the glassy basis of the whole rock? This devitrification might be shown by the appearance of numerous microscopic hairs, rods, bundles of feather-like irregular or granular aggregations (p. 204). 4th, In what order did the minerals crystallize? This may often be made out with a microscope, as, for instance, where one mineral is inclosed within another (p. 204).[57] 5th, What is the nature of any alteration which the rock may have undergone? In a vast number of cases the slices show abundant evidence of such alteration: felspar passing into granular kaolin, augite changing into viridite, olivine into serpentine, while secondary calcite, epidote, quartz, and zeolites run in minute veins or fill up interstices of the rock (p. 587). 6th, Is the rock a fragmental one; and if so, what is the nature of its component grains (pp. 224–225)? Is any trace of organic remains to be detected?

§ iv.—General outward or Megascopic (Macroscopic) Characters of Rocks[58]

1. **Structure.**[59]—The different kinds of rock-structures dis-

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[57] It is possible, however, that a crystal inclosed within another may sometimes have crystallized there out of a portion of the surrounding magma of the rock which has been inclosed within the larger crystal (postea p. 514).

[58] The following general text-books on rocks may be referred to: Macculloch, "A Geological Classification of Rocks," etc., London, 1821. B. von Cotta, "Rocks Classified and Described," translated by Lawrence, London, 1866. Zirkel, "Lehrbuch der Petrographie," two vols. Bonn, 1866. Senft, "Classification der Felsarten," Breslau, 1857; "Die Krystallinischen Felsgemengtheile," Berlin, 1868. Kenngott, "Elemente der Petrographie," Leipz., 1868. A. von Lasaulx, "Elemente der Petrographie," Bonn, 1875. Bischof, "Chemical Geology," translated for Cavendish Society, 1854–59, and supplement, Bonn, 1871. Roth, "Allgemeine und Chemische Geologie," Berlin, 1879. Other works in which the microscopical characters are more specially treated of, are enumerated on p. 193.

[59] In the 3d edition of Jukes' "Student's Manual of Geology" (1871), p. 93, it was proposed to reserve the term "Structure" for large features, such as characterize rock-blocks, and to use the term "Texture" for the minuter characters,

tinguishable by the unaided eye are denoted either by ordinary descriptive adjectives, or by terms derived from rocks in which the special structures are characteristically developed, such as granitoid, brecciated, shaly. It must be borne in mind, however, that the external character of a rock does not always supply us with its true internal structure, which may be gained only by microscopic examination. This is of course more especially true of the close-grained kinds, where to the naked eye no definite structure is discernible. Some of the definitions originally founded on external appearance have been considerably modified by microscopic investigation. Many compact rocks, for instance, have been proved to be wholly crystalline.

The same rock-mass may show very different structures and textures in different parts of its extent. This is true alike of sedimentary and igneous materials. It may be observed even in the several portions of one continuous mass of erupted rock—variations in the rate of cooling, in temperature, and other circumstances have combined to produce sometimes the most extraordinary textural and even structural, as well as chemical and mineralogical contrasts in a boss or sheet of igneous rock.[60] Hence the student must be on his guard against concluding that two portions of rock strikingly unlike each other in outward appearance cannot be portions of one original continuous mass.

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such as can be judged of in hand specimens. M. De Lapparent makes a similar distinction (Traité, p. 602, note). But the practice of using the word structure as it is employed above in the text, has received such a support from the petrographers of Germany that though I still think it would be preferable to distinguish between *texture* and *structure*, I have adopted what has now the sanction of common usage.

[60] See Book IV. Part VII.; G. F. Becker, Amer. Journ. Sci. xxxiii. (1887), p. 50. J. H. L. Vogt, Geol. Fören. Förhand. Stockholm, xiii. (1891).

Crystalline (Phanerocrystalline), consisting wholly or chiefly of crystalline particles or crystals.[61] Where the individual elements of the rocks are of large size, the structure is *coarse-crystalline* (*granitic*), as in many granites. When the particles are readily visible to the naked eye, and are tolerably uniform in size, as in marble, many granites and dolomites, the rock is said to be granular-crystalline. Successive stages in the diminution of the size of the particles may be traced until these are no longer recognizable with the naked eye, and the structure must then be resolved with the microscope (*fine-crystalline*, *micro-crystalline*, *crypto-crystalline*). Fine-grained rocks may also be called *compact*, though this term is likewise applicable to the more close-grained varieties of the fragmental series. The microscopic characters of such rocks should always be ascertained where possible.[62]

Many crystalline rocks consist not only of crystals, but of a magma or paste, in which the crystalline particles are seen by the naked eye to be imbedded. It is of course impossible, except from analogy, to determine macroscopically what may be the nature of this magma. It may be entirely composed of minute crystals, or may consist of various crystallitic products of devitrification. Its intimate structure can only be ascertained with the microscope. But its existence is often strikingly manifest even to the unassisted eye, for in what are termed "porphyries" it forms a large part of their mass. The term "*ground-mass*" is employed to denote this megascopic matrix. Microscopic examination shows that a ground-mass may consist of minute crystals,

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[61] Prof. Rosenbusch proposed the term "holocrystalline" for rocks in which there is no morphous material among the crystalline constituents.

[62] On the crystallization of igneous rocks, see J. P. Iddings, Bull. Phil. Soc. Washington, xi. (1889), p. 71.

or crystallites, or granules and filaments, or glass, or combinations of these in various proportions. (See pp. 194, 207.)

Lithoid, compact and stony in aspect, with no very distinct crystalline structure. The term is especially applied to the devitrified condition of once glassy rocks, such as obsidians, which have assumed the character of perlites or felsites.

Granitic (Granitoid), thoroughly crystalline, and consisting of crystals approximately uniform in size, as in granite. This structure is characteristic of many eruptive rocks. Though usually distinctly recognizable by the naked eye ("macromerite" of Vogelsang[63]), it sometimes becomes very fine ("micromerite"), and may be only recognizable with the microscope as thoroughly crystalline (microgranitic); at other times it passes into a porphyritic or porphyroid character by the appearance of large crystals dispersed through a general ground-mass.

Pegmatitic (Pegmatoid, Graphic), exhibiting the peculiar arrangement of crystalline constituents seen in pegmatite or graphic granite (p. 275), where the quartz and felspar have crystallized simultaneously so as to be inclosed within each other. This structure may be seen on a large scale in many massive veins of pegmatite; where it takes an exceedingly minute form it is known as micropegmatitic (Fig. 5). Such microscopic intergrowth of quartz and felspar is characteristic of large masses of eruptive rock (micropegmatite, granophyre).

Fig. 5.—Micropegmatitic Structure. Granophyre, Mull. (Magnified.)

[63] Z. Deutsch. Geol. Ges. xxiv. p. 534.

Aphanitic, a name given to the very close texture exhibited by some igneous rocks (diabases, diorites) where the component ingredients cannot be determined except with the microscope.

Porphyritic (Porphyroid), composed of a compact or finely crystalline ground-mass, through which larger crystals of earlier consolidation,[64] often of felspar, are dispersed (Fig. 6). This and the granitic structure are the two

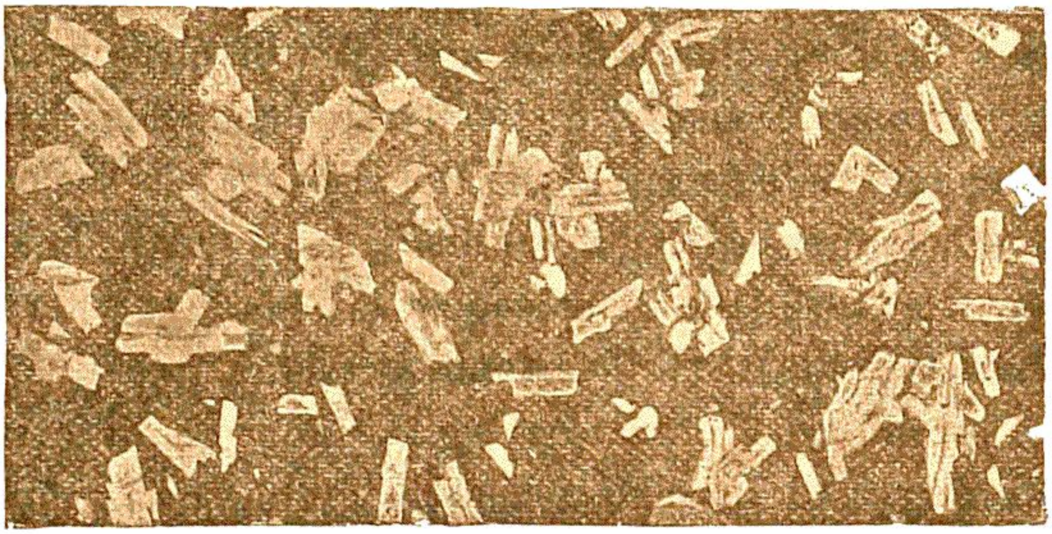

Fig. 6.—Porphyritic Structure. (Nat. size.)

great structure-types of the eruptive rocks. By far the larger number of these rocks belong to the porphyritic type. Microscopic research has thrown much light on the nature of the ground-mass of porphyritic rocks. Vogelsang proposed to classify these rocks in three divisions:[65] 1st, *Granophyre*, where the ground-mass is a microscopic crystalline mixture of the component minerals with absence or sparing development of an imperfectly individualized magma (see p. 209); 2d, *Felsophyre*, having usually an imperfectly individualized or felsitic magma for the ground-mass (pp. 208,

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[64] Phenocrysts, Iddings, Bull. Phil. Soc. Washington, ii. (1889), p. 73.

[65] Vogelsang, loc. cit. Compare the classification into granitoid and trachytoid, p. 271.

211); 3d, *Vitrophyre*, where the ground-mass is a glassy magma (pp. 204, 212). The second subdivision embraces most of the porphyries, and a very large number of eruptive rocks of all ages.[66]

Segregated.—In granite and other crystalline massive rocks, vein-like portions, coarser (or finer) in texture than the rest of the mass, may be observed. These belong to the last phase of consolidation, when segregations from the original molten or viscous magma took place along certain lines or round particular centres, where the individual minerals crystallized out from the general mass. They have been sometimes termed "segregation," or "exudation" veins. They are to be distinguished from the veins, usually of finer and more acid material, which ramify through a mass of igneous rock and probably represent portions of the original molten magma which remained still liquid and were injected into rents of the already consolidated parts. These are the true "contemporaneous veins" (Book IV. Part VII.)

Granular—a somewhat vague term applied to rocks composed of approximately equal grains, which are sometimes worn fragments, as in sandstone, sometimes crystalline particles, as in granite and marble. This texture may become so fine as to pass insensibly into compact.[67] The peculiar granular structure found so abundantly among metamorphic rocks which have been intensely crushed and in which there seems to have been a process of recrystalli-

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[66] According to Rosenbusch the porphyritic massive rocks are those in which, during the different stages of their production, the same minerals have been formed more than once. Neues Jahrb. 1882 (ii.), p. 14.

[67] As applied to massive (eruptive) rocks, Rosenbusch would restrict the term granular to those in which each individual constituent separated out during but one definite stage of the process of rock-building. Loc. cit.

zation among the powdered particles, has been termed granulitic (p. 210). This word, however, is liable to the objection that in Germany it is applied to rocks bearing that structure while in France it is used for a holocrystalline granite.[68]

Vitreous or glassy, having a structure like that of artificial glass, as in obsidian. Among the crystalline rocks there is often present a variable amount of an amorphous ground-mass, which may increase until it forms the main part of the substance. The nature of this amorphous portion is described at pp. 203, 212. Its most obvious megascopic condition is that of a volcanic glass. Most vitreous rocks present, even to the naked eye, dispersed grains, crystals, or other inclosures. Under the microscope, they are found to be often crowded with minute crystals and imperfect or incipient crystalline forms (pp. 194, 205). Resinous is the term applied to vitreous rocks having the lustre of pitchstone, and to others which are still less vitreous. Devitrification is the conversion of the vitreous into a crystalline or lithoid structure (pp. 206, 214).

Streaked, arranged in streaky inconstant lines (Germ. *Schlieren*), either parallel or convergent, and often undulating. This structure, conspicuously shown by the lines of flow in vitreous rocks (flow-structure, fluxion-structure, fluidal-structure) is less marked where the materials have assumed definite crystalline forms. It can be seen on a minute scale, however, in many crystalline masses when examined with the microscope (p. 211).

Banded, arranged in parallel bands, distinguished from each other by color, texture, structure or composition; char-

[68] Michel-Lévy, Ann. des Mines, viii. (1875), p. 387; "Structure et Classification des Roches Eruptives," 1889, p. 14.

acteristic of many gneisses, and of jaspers, flints, hälleflintas and other flinty rocks. This term may frequently be applied to the flow-structure of igneous rocks referred to in the previous paragraph, likewise to the segregation veins of eruptive bosses and sheets, and to the parallel arrangement of materials produced in rocks which have under intense mechanical pressure been crushed and sheared. With the naked eye it is often hardly possible to distinguish between the banded structure of devitrified igneous rocks and that resulting from intense mechanical deformation.

Mylonitic, a term introduced to denote the peculiar granular structure of rocks which have undergone intense crushing. The materials have been reduced to minute grains which have not recrystallized as they have done in the granulitic structure. Many remarkable examples of this structure have been observed among the schists of the Scottish Highlands.

Spherulitic, composed of, or containing small globules or spherules which may be colloid and isotropic, or more or less distinctly crystalline, particularly with an internal fibrous divergent structure (Figs. 7, 17). This structure occurs in vitreous rocks, where it is one of the stages of devitrification in obsidian, pitchstone, etc.[69] (p. 214).

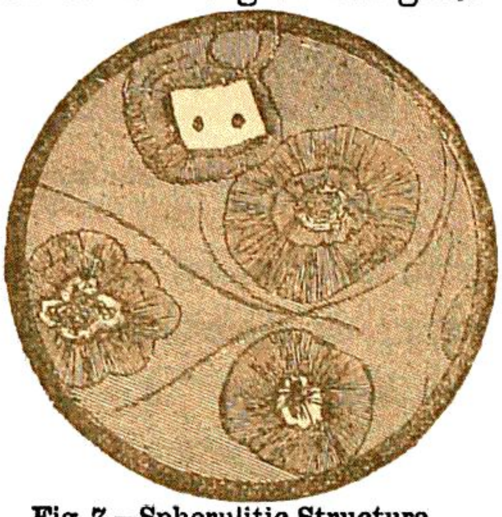

Fig. 7.—Spherulitic Structure. (Magnified.)

[69] On the constitution and origin of spherulite in acid eruptive rocks, see Whitman. Cross, Phil. Soc. Washington, xi. p. 411 (1891), and J. P. Iddings, op. cit. p. 445. Quartz assumes in some rocks (*e.g.* banded eurites) a finely globular structure which was developed before the cessation of the motion that produced flow-structure, and which, according to M. Michel-Lévy, may be regarded as connecting the colloid and crystallized conditions of silica. Bull. Soc. Géol. France (3), v. p. 140.

The term lithophyse has been applied by F. von Richthofen to large bladder-like spherulites wherein inter-spaces lined with crystals occur between the successive concentric internal layers.[70] Many ancient rhyolites present an aggregate of nodular bodies (Pyromeride) due originally to devitrification and subsequently more or less altered especially by the deposition of silica within them (postea, p. 280).

Orbicular structure is one in which the component minerals of a rock have crystallized in such a way as to

Fig. 8.—Orbicular Structure. Napoleonite, Corsica. (Nat. Size.)

form spheroidal aggregations sometimes with an internal radial or concentric grouping. It is typically seen in the napoleonite or ball-diorite (kugeldiorite, orbicular diorite, p. 287) of Corsica (Fig. 8), but occurs in other rocks, sometimes even in granite.

Perlitic (Figs. 9 and 20), having the structure of the rock formerly termed perlite, wherein between minute rec-

[70] Jahrb. K. K. Geol. Reichsanst, 1860, p. 180. See Iddings, 7th Ann. Rep. U. S. Geol. Surv. (1885–86), p. 249. Amer. Journ. Sci. xxxiii. (1887), p. 36.

tilinear fissures the substance of the mass has assumed, during the contraction resulting from cooling, a finely globular character, not unlike the spheroidal structure seen in weathered basalt which is also a phenomenon of contraction during the cooling and consolidation of an igneous rock.

Fig. 9.—Perlitic Structure. (Magnified.)

Horny, flinty, having a compact, homogeneous, dull texture, like that of horn or flint, as in chalcedony, jasper, flint, and many hälleflintas and felsites.

Cavernous (porous), containing irregular cavities due, in most cases, to the abstraction of some of the minerals; but occasionally, as in some limestones (sinters), dolomites and lavas, forming part of the original structure of the rock.

Cellular.—Many lavas, ancient and modern, have been saturated with steam at the time of their eruption, and in consequence of the segregation and expansion of this imprisoned vapor, have had spherical cavities developed in their mass. When this cellular structure is marked by comparatively few and small holes, it may be called vesicular; where the rock consists partly of a roughly cellular, and partly of a more compact substance intermingled, as in the slag of an iron furnace, it is said to be slaggy; portions where the cells occupy about as much space as the solid part, and vary much in size and shape, are called scoriaceous, this being the character of the rough clinker-like scoriæ of recent lava-streams; when the cells are so much more numerous than the solid part, that the stone would almost or quite float on water, the structure is called pumiceous, the term *pumice* being applied to the froth-like part of obsidian. As the cellular structure can only be developed while the rock is still liquid, or at least viscid, and as, while in this condition, the mass is often still moving away from its point of emission, the cells are not infrequently elongated in the direction of movement. Subsequently water, infiltrating through the

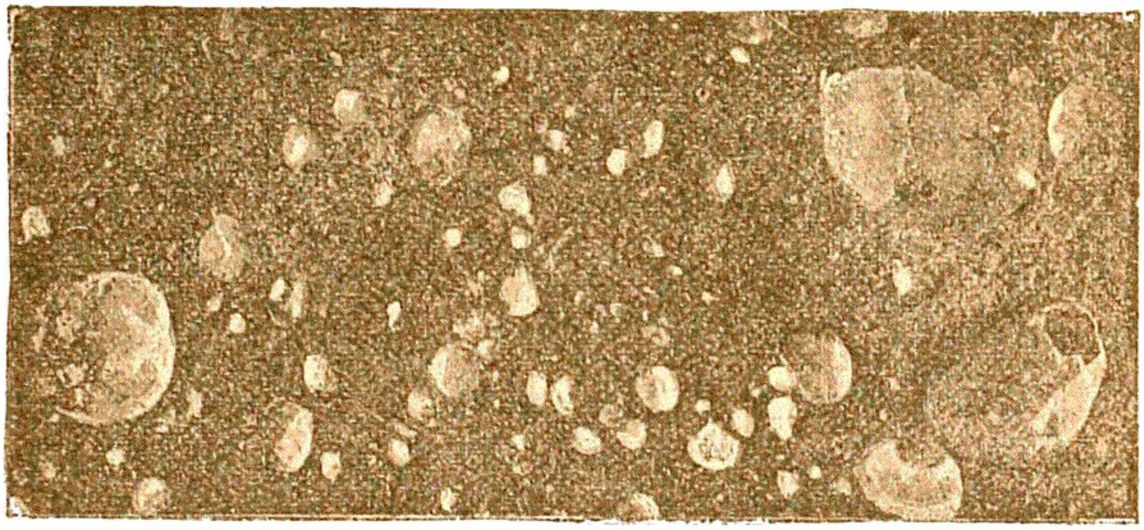

Fig. 10.—Amygdaloidal Structures; Porphyrite, Old Red Sandstone, Ayrshire. (Nat. size.)

rock, deposits various mineral substances (calcite, quartz, chalcedony, zeolites, etc.) from solution, so that the flattened and elongated almond-shaped cells are eventually filled up. A cellular rock which has undergone this change is said to be an amygdaloid, or amygdaloidal, and the almond-like kernels are known as amygdales (Fig. 10). Where the cells or cavernous spaces of a rock are lined with crystals and empty inside they are said to be druses or drusy cavities.

Cleaved, having a fissile structure superinduced by pressure and known as cleavage (see pp. 531, 532). The planes of cleavage are independent of those of bedding, though they may coincide with them. A cleaved structure is best seen in fine-grained material, and is typically developed in roofing-slate, but it may occur in any compact igneous rock.

Foliated, consisting of minerals that have crystallized in approximately parallel, lenticular, and usually wavy layers or folia. Rocks of this kind commonly contain layers of mica, or of some equivalent readily cleavable mineral, the cleavage-planes of which coincide generally with the planes of foliation. Gneiss, mica-schist and talc-schist are characteristic examples. So distinctive, indeed, is this structure in schists, that it is often spoken of as schistose. In gneiss, it attains its most massive form; in chlorite-schist and some other schists, it becomes so fine as to pass into a kind of minutely scaly texture, often only perceptible with the microscope, the rock having on the whole a massive structure.

Fibrous, consisting of one or more minerals composed of distinct fibres. Sometimes the fibres are remarkably regular and parallel, as in fibrous gypsum, and veins of chrysotile, fibrous aragonite or calcite (satin-spar); in other instances, they are more tufted and irregular, as in asbestos and actinolite-schist.

Clastic, fragmental, composed of detritus (p. 214). Rocks possessing this character have, in the great majority of cases, been formed in water, and their component fragments are usually more or less rounded or water-worn. Different names are applied, according to the form or size of the fragments. Brecciated, composed, like a breccia, of angular fragments, which may be of any degree of coarseness. Agglomerated, consisting of large, roughly rounded and tumultuously grouped blocks, as in the agglomerate filling old volcanic funnels. Conglomerated (Conglomeratic), made up of well-rounded blocks or pebbles; rocks having this character have been formed by and deposited in water. Pebbly, containing dispersed water-worn pebbles, as in many coarse sandstones, which thus by degrees pass into conglomerates. Psammitic, or sandstone-like, composed of rounded grains, as in ordinary sandstone: when the grains are larger (often sharp and somewhat angular) the rock is gritty, or a grit. Muddy (pelitic), having a texture like that of dried mud. Cryptoclastic or compact, where the grains are too minute to reveal to the naked eye the truly fragmental character of the rock, as in fine mudstones and other argillaceous deposits.

Concretionary, containing, or consisting of mineral matter, which has been collected, either from the surrounding rock or from without, round some centre, so as to form a nodule or irregularly shaped lump. This aggregation of material is of frequent occurrence among water-formed rocks, where it may be often observed to have taken place round some organic centre, such as a leaf, cone, shell, fish-bone, or other relic of plant or animal. (Book IV. Part I.) Among the most frequent minerals found in concretionary forms as constituents of rocks, are calcite, siderite, pyrite, marcasite, and various forms of silica. In a true concretion, the material at the centre has been deposited first, and has increased by additions from without, either during the formation of the inclosing rock, or by subsequent concentration and aggregation. Where, on the other hand, cavities and fissures have been filled up by the deposition of materials on their walls, and gradual growth inward, the result is known as a secretion. Amygdales and the successive coatings of mineral veins are examples of the latter process.

Septarian—a structure often exhibited by concretions of limestone and clay-ironstone which in consolidating have shrunk and cracked internally. These shrinkage-cracks radiate in an irregular way from the middle toward the circumference, but die out before reaching the latter (Fig. 26). Usually they have been filled with some subsequently infiltrated mineral, notably calcite.

Oolitic, a structure like fish-roe, formed of spherical grains, each of which has an internal radiating and concentric structure, and often possesses a central nucleus of some foreign body. This structure is specially found among limestones (see p. 262). When the grains are as large as peas, the structure is termed pisolitic.

Various structures which affect large masses of rock rather than hand-specimens will be found described in Book IV. But a few of the more important may be included here.

Massive, unstratified, having no arrangement in definite layers or strata. Lava, granite, and generally all crystalline rocks which have been erupted to the surface, or have solidified below from a state of fusion are massive rocks.

Stratified, bedded, composed of layers or beds lying parallel to each other, as in shale, sandstone, limestone, and other rocks which have been deposited in water. Successive streams of lava, poured one upon another, have also a bedded arrangement. Laminated, consisting of fine, leaf-like strata or laminæ; this structure being characteristically exhibited in shales, is sometimes also called shaly.

Jointed, traversed by the divisional planes termed Joints which are fully treated of in Book IV. Part II.

Columnar, divided into prismatic joints or columns. This structure is typically represented among the basalts and other basic lavas (p. 883 and Figs. 230–232), but it may also be observed as an effect of contact-metamorphism among stratified rocks which have been invaded by intrusive masses (Book IV. Part VIII.)

2. **Composition.**—Before having recourse to chemical or microscopic analysis, the geologist can often pronounce as to the general chemical or mineralogical nature of a rock. Most of the terms which he employs to express his opinion are derived from the names of minerals, and in almost all cases are self-explanatory. The following examples may suffice. Calcareous, consisting of or containing carbonate of lime. Argillaceous, consisting of or containing clay. Felspathic, having some form of felspar as a main constituent. Siliceous, formed of or containing silica; usually applied to the chalcedonic forms of this cementing oxide. Quartzose, containing or consisting entirely of some form of quartz. Carbonaceous, containing coaly matter, and hence usually associated with a dark color. Pyritous, containing diffused disulphide of iron. Gypseous, containing layers, nodules, strings or crystals of calcium-sulphate. Saliferous, containing beds of, or impregnated with rock-salt. Micaceous, full of layers of mica-flakes.

As rocks are not definite chemical compounds, but mixtures of different minerals in varying proportions, they exhibit many intermediate varieties. Transitions of this kind are denoted by such phrases as "granitic gneiss," that is, a gneiss in which the normal foliated structure is nearly merged into the massive structure of granite; ' argillaceous limestone''—a rock in which the limestone is mixed with clay; ''calcareous shale''—a fissile rock, consisting of clay with a proportion of lime. It is evident that such rocks may graduate so insensibly into each other, that no sharp line can be drawn between them either in the field or in their terminology.

As already alluded to, and as will be more fully explained in later pages, the progress of research goes to show that even in the same mass of eruptive rock considerable differences of chemical composition may be found. These differences seem to point to some separation of the constituents, by gravity or otherwise, before consolidation. Thus the picrite of Bathgate shades upward into a rock in which the heavy magnesian silicates are replaced in large measure by felspars.[71] Mr. Iddings has recently called attention to some remarkable gradations of composition among the volcanic rocks of the Tewar Mountains, New Mexico, where he believes a series of intermediate varieties to be traceable from obsidian at the one end to basalt at the other.[72] A remarkable instance of a similar kind is described by Mr. Teall and Mr. Dakyns from the Scottish Highlands.

3. **State of Aggregation.**—The hardness or softness of a rock, in other words, its induration, friability, or the degree of aggregation of its particles, may be either original or acquired. Some rocks (sinters, for example) are soft at first and harden by degrees; the general effect of exposure, how-

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[71] Trans. Roy. Soc. Edin. vol. xxix. (1879), p. 504.

[72] Bull. U. S. Geol. Surv. No. 66 (1890), Bull. Phil. Soc. Washington, xi. (1890), pp. 65, 191, and postea, pp. 457, 458. Teall and Dakyns, Quart. Journ. Geol. Soc. 1892.

ever, is to loosen the cohesion of the particles of rocks. A rock which can easily be scratched with the nail is almost always much decomposed, though some chloritic and talcose schists are soft enough to be thus affected. Compact rocks which can easily be scratched with the knife, and are apparently not decomposed, may be fine-grained limestones, dolomites, ironstones, mudstones, or some other simple rocks. Crystalline rocks, except limestone, cannot, as a rule, be scratched with the knife unless considerable force be used. They are chiefly composed of hard silicates, so that when an instance occurs where a fresh specimen can be easily scratched, it will usually be found to be a limestone (pp. 148, 139, 149). The ease with which a rock may be broken is the measure of its frangibility. Most rocks break most easily in one direction; attention to this point will sometimes throw light upon their internal structure.

Fracture is the surface produced when a rock is split or broken, and depends for its character upon the texture of the mass. Finely granular, compact rocks are apt to break with a splintery fracture where wedge-shaped plates adhere by their thicker ends to, and lie parallel with the general surface. When the rock breaks off into concave and convex rounded shell-like surfaces, the fracture is said to be conchoidal, as may be seen in obsidian and other vitreous rocks and in exceedingly compact limestones. The fracture may also be foliated, slaty, or shaly, according to the structure of the rock. Many opaque, compact rocks are translucent on the thin edges of fracture, and afford there, with the aid of a lens, a glimpse of their internal composition. A rock is said to be flinty, when it is hard, close-grained, and breaks with a smooth or conchoidal fracture like flint; friable, when it crumbles down like dry clay or chalk; plastic, when, like moist clay, it can be worked into shapes; pulverulent, when it falls readily to powder; earthy, when it is decomposed into loam or earth; incoherent or loose, when its particles are quite separate, as in dry blown sand.

4. **Color and Lustre.**—These characters vary so much, even in the same rock, according to the freshness of the surface examined, that they possess but a subordinate value. Nevertheless, when cautiously used, color may be made to afford valuable indications as to the probable nature and composition of rocks. It is, in this respect, always desirable to compare a freshly-broken with a weathered piece of the rock.[73]

White indicates usually the absence or a comparatively small amount of the heavy metallic oxides, especially iron. It may either be the original color, as in chalk and calc-sinter, or may be developed by weathering, as in the white crust on flints and on many porphyries. *Gray* is a frequent color of rocks which, if quite pure, would be white, but which acquire a grayish tint by admixture of dark silicates, organic matter, diffused pyrites, etc. *Blue* or *bluish-gray* is a characteristic tint of rocks through which iron-disulphide is diffused in extremely minute subdivision. But as a rule it rapidly disappears from such rocks on exposure, especially where they contain organic matter also. The stiff blue clay of the sea-bottom which is colored by iron-disulphide becomes reddish-brown when dried, and then shows no trace of sulphide.[74] *Black* may be due either to the presence of carbon (when weathering will not change it much), or to

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[73] Alterations of the colors of minerals and rocks are effected by heat and even by sunlight. See Janettaz, Bull. Soc. Géol. xxix. (1872), p. 300.

[74] J. Y. Buchanan, Brit. Assoc. 1881, p. 584.

some iron-oxide (magnetite chiefly), or some silicate rich in iron (as hornblende and augite). Many rocks (basalts and melaphyres particularly) which look quite black on a fresh surface, become red, brown or yellow on exposure, black being comparatively seldom a weathered color. *Yellow* (or *Orange*), as a dull earthy coloring matter, almost always indicates the presence of hydrated peroxide of iron. In modern volcanic districts it may be due to iron-chloride, sulphur, etc. Bright, metallic, gold-like yellow is usually that of iron-disulphide. *Brown* is the normal color of some carbonaceous rocks (lignite), and ferruginous deposits (bog-iron-ore, clay-ironstone, etc.). It very generally, on weathered surfaces, points to the oxidation and hydration of minerals containing iron. *Red*, in the vast majority of cases, is due to the presence of anhydrous peroxide of iron. This mineral gives dark blood-red to pale flesh-red tints. As it is liable, however, to hydration, these hues are often mixed with the brown, orange and yellow colors of limonite.[75] *Green*, as the prevailing tint of rocks, occurs among schists, when its presence is usually due to some of the hydrous magnesian silicates (chlorite, talc, serpentine). It appears also among massive rocks, especially those of older geological formations, where hornblende, olivine, or other silicates have been altered. Among the sedimentary rocks, it is principally due to ferrous silicate (as in glauconite). Carbonate of copper colors some rocks emerald- or verdigris-green. The mottled character so common among many stratified rocks is frequently traceable to unequal weathering, some portions of the iron being more oxidized than others; while some, on the other hand, become deoxidized

[75] See I. C. Russell, Bull. U. S. Geol. Surv. No. 52 (1889).

from the reducing action of decaying organic matter, as in the circular green spots so often found among red strata.

Lustre, as an external character of rocks, does not possess the value which it has among minerals. In most rocks, the granular texture prevents the appearance of any distinct lustre. A completely *vitreous* lustre without a granular texture, is characteristic of volcanic glass. A *splendent semi-metallic* lustre may often be observed upon the foliation planes of schistose rocks and upon the laminæ of micaceous sandstones. As this silvery lustre is almost invariably due to the presence of mica, it is commonly called distinctively *micaceous*. A *metallic* lustre is met with sometimes in beds of anthracite; more usually its occurrence among rocks indicates the presence of metallic oxides or sulphides. A *resinous* lustre is characteristic of many pitchstones. *Lustre-mottling* is a term applied to the interrupted sheen on the cleavage faces of minerals which have inclosed much smaller crystals or grains of other minerals. It is well seen on the surfaces of some of the constituents of serpentine rocks.

5. **Feel and Smell.**—These minor characters are occasionally useful. By the feel of a mineral or rock is meant the sensation experienced when the fingers are passed across its surface. Thus hydrous magnesian silicates have often a marked soapy or greasy feel. Some sericitic mica-schists show the same character. Trachyte received its name from its characteristic rough or harsh feel. Some rocks adhere to the tongue, a quality indicative of their tendency to absorb water.

Smell.—Many rocks, when freshly broken, emit distinctive odors. Those containing volatile hydrocarbons give sometimes an appreciable *bituminous* odor, as is the case with certain eruptive rocks, which in central Scotland have been intruded through coal-seams and carbonaceous shales. Limestones have often a *fetid* odor; rocks full of decomposing sulphides are apt to give a *sulphurous* odor; those which are highly siliceous yield, on being struck, an *empyreumatic* odor. It is characteristic of argillaceous rocks to emit a strong earthy smell when breathed upon.

6. **Specific Gravity.**—This is an important character among rocks as well as among minerals. It varies from 0·6 among the hydrocarbon compounds to 3·1 among the basalts. As already stated, the average specific gravity of the rocks of the earth's crust may be taken to be about 2·5, or from that to 3·0. Instruments for taking the specific gravity of rocks have been already (p. 154) referred to.

7. **Magnetism** is so strongly exhibited by some crystalline rocks as powerfully to affect the magnetic needle, and to vitiate observations with this instrument. It is due to the presence of magnetic iron, the existence of which may be shown by pulverizing the rock in an agate mortar, washing carefully the triturated powder, and drying the heavy residue, from which grains of magnetite or of titaniferous magnetic iron may be extracted with a magnet. This may be done with any basalt (p. 155). A freely swinging magnetic needle is of service, as by its attraction or repulsion it affords a delicate test for the presence of even a small quantity of magnetic iron.

§ v. Microscopic Characters of Rocks

No department of Geology has been more advanced in recent years than Lithology, and this has been mainly due to the introduction of the microscope as an instrument for investigating minute internal structure. As far back as the year 1827, a method of making thin transparent sections of fossil wood, and mounting them on glass with Canada balsam, had been devised by William Nicol of Edinburgh, and was employed by Henry Witham in his "History of Fossil Vegetables." [76]

It was not, however, until 1856 that Mr. H. C. Sorby, applying this method to the investigation of minerals and rocks, showed how many and important were the geological questions on which it was calculated to shed light.[77] Reference will be made in subsequent pages to the remarkable results then announced by him. To the publication of his memoir the subsequent rapid development of the microscopic study of rocks may be distinctly traced. The microscopic method of analysis is now in use in every country where attention is paid to the history of rocks.[78]

In § iii. p. 161 information has been given regarding the

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[76] Small 4to, Edinburgh, 1831. This work, though dedicated to Nicol, does not distinctly recognize him as the actual inventor of the process of slicing mineral substances for microscopic investigation. All that was original in Witham's researches he owed either directly or indirectly to Nicol.

[77] Brit. Assoc. 1856, Sect. p. 78. Quart. Journ. Geol. Soc. xiv. 1858. Micr. Journ. xvii. (1877), p. 113.

[78] Among the best text-books on this subject the following may be mentioned:—"Mikroskopische Beschaffenheit der Mineralien und Gesteine," F. Zirkel, 1 vol. 1873. "Mikroskopische Physiographie der Mineralien und Gesteine," H. Rosenbusch, 2 vols. 2d Edit. 1885–87, and the English translation of the first volume quoted on p. 161; likewise the Tables translated by F. H. Hatch quoted on p. 161. "Elemente der Petrographie," A. von Lasaulx, 1875. "Minéralogie micrographique: roches éruptives françaises," Fouqué and Michel-Lévy, 2 vols. 4to, Paris, 1879. "Microscopical Petrography," Zirkel, being vol. vi. of the Geol. Explor. of 40th Parallel, Washington, 1876. "British Petrography," J. J. H. Teall, London, 1888. "Les Minéraux des Roches," Michel-Lévy and Lacroix, Paris, 1888. The volumes for the last fifteen or twenty years of the Quarterly Journal of the Geological Society, Geological Magazine, Neues Jahrbuch für Mineralogie, etc., Zeitschrift der Deutschen Geologischen Gesellschaft, Bulletin de la Société géologique de France, Jahrbuch der K. K. Geologischen Reichsanstalt (Vienna), contain numerous papers on the microscopic structure of rocks. Rutley's "Study of Rocks," 1879, and his "Rock-forming Minerals," 1888; Cole's "Aids in Practical Geology," 1891; and Hatch's "Petrology—Igneous Rocks," 1891, are useful handbooks. The manual of Rosenbusch and the work of Fouqué and Michel-Lévy, contain a tolerably ample bibliography of the subject, to which the student is referred. The titles of some of the more important memoirs which have recently appeared will be given in footnotes.

preparation of sections of rocks for microscopical examination, the methods of procedure in the practice of this part of geological research, and some of the terms employed in the following pages.

1. *Microscopic Elements of Rocks*

Rocks when examined in thin sections with the microscope are found to be composed of or to contain various elements, of which the more important are, 1st, crystals, or crystalline substances; 2d, glass; 3d, crystallites; 4th, detritus.

A. Crystals or Crystalline Substances.—Rock-forming minerals, when not amorphous, may be either crystallized in their proper crystallographic forms (idiomorphic), or while possessing a crystalline internal structure, may present no definite external geometrical form (allotriomorphic, p. 209). The latter condition is more prevalent, seeing that minerals have usually been developed round and against each other, thus mutually hindering the assumption of determinate crystallographic contours. Other causes of imperfection are fracture by movement in the original magma of the rock, and partial solution in that magma (Fig. 12), as in the corroded quartz of quartz-porphyries and rhyolites, and the hornblende crystals of basalts. The ferro-magnesian minerals of earlier consolidation among basalts and andesites, are sometimes surrounded with a dark shell called the corrosion-zone. In some rocks, such as granite, the thoroughly crystalline character of the component ingredients is well marked, yet they less frequently present the definite isolated crystals so often to be observed in porphyries and in many old and modern volcanic rocks. Among thoroughly crystalline rocks, good crystals of the component minerals may be obtained from fissures and cavities in which there has been room for their formation. It is in the "drusy" cavities of granite, for example, that the well-defined prisms of felspar, quartz, mica, topaz, beryl and other minerals are found. Successive stages in order of appearance or development can readily be observed among the crystals of rocks. Some appear as large, but frequently broken, or corroded forms. These have evidently been formed first. Others are smaller but abundant, usually unbroken, and often disposed in lines. Others have been developed by subsequent alteration within the rock.[79]

A study of the internal structure of crystals throws light not merely on their own genesis, but on that of the rocks of which they form part, and is therefore well worthy of the attention of the geologist. That many apparently simple crystals are in reality compound, may not infrequently be detected by the different condition of weathering in the two opposite parts of a twin on an exposed face of rock. The internal structure of a crystal modifies the action of solvents on its exterior (*e.g.* weathered surfaces of calcite, aragonite and felspars). Crystals may occasionally be observed built up of rudimentary "microlites," as if these were the simplest forms in which the molecules of a mineral begin to appear (p. 205).

A microscopic examination of some rocks shows that a subsequent or secondary growth of different minerals has taken place after their original crystalline form was complete. These later additions are in optical continuity with the original crystal, and sometimes have taken place even upon worn or imperfect forms. They may be occasionally detected among the silicates of igneous rocks, and also even

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[79] Fouqué and Michel-Lévy, "Min. Micrograph." p. 151.

among the sandgrains of sandstones which have thus had their rounded forms converted into crystallographic faces.[80]

Crystalline minerals are seldom free from extraneous inclusions. These are occasionally large enough to be readily seen by the naked eye. But the microscope reveals them in many minerals in almost incredible quantity. They are, α, vesicles containing gas; β, vesicles containing liquid; γ, globules of glass or of some lithoid substance; δ, crystals; ε, filaments, or other indefinitely-shaped pieces, patches, or streaks of mineral matter.

α. Gas-filled cavities—are most frequently globular or elliptical, and appear to be due to the presence of gas or steam in the crystal at the time of consolidation. Zirkel estimates them at 360,000,000 in a cubic millimetre of the hauyne from Melfi.[81] In some instances the cavity has a geometric form belonging to the crystalline system of the inclosing mineral. Such a space defined by crystallographic contours is a *negative crystal*. A cavity filled with gas contains no bubble, and its margin is marked by a broad dark band. The usual gas is nitrogen, with traces of oxygen and carbon-dioxide; sometimes it is entirely carbon-dioxide or hydrogen and hydrocarbons.

β. Vesicles containing liquid (and gas).—As far back as the year 1823, Brewster studied the nature of certain fluid-bearing cavities in different minerals.[82] The

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80 H. C. Sorby, Presidential Address, Geol. Soc. 1880, p. 62. R. D. Irving and C. R. Van Hise "On secondary enlargements of Mineral Fragments in certain rocks." Bull. U. S. Geol. Surv. No. 8 (1884). J. W. Judd, Quart. Journ. Geol. Soc. xlv. (1889), p. 175.

81 "Mik. Beschaff." p. 86.

82 Edin. Phil. Journ. ix. p. 94. Trans. Roy. Soc. Edin. x. p. 1. See also W. Nicol, Edin. New Phil. Journ. (1828), v. p. 94; De la Vallée Poussin and Renard, Acad. Roy. Belg. 1876, p. 41; Hartley, Journ. Chem. Soc. ser. 2, xiv. 137; ser. 3, ii. p. 241; Microscop. Journ. xv. p. 170; Brit. Assoc. 1877, Sect. p. 232.

first observer who showed their important bearing on geological researches into the origin of crystalline rocks was Mr. Sorby, in whose paper, already cited, they occupy a prominent place. Vesicles entirely filled with liquid are distinguished by their sharply-defined and narrow black borders. Vesicular spaces containing fluid may be noticed in many artificial crystals formed from aqueous solutions (crystals of common salt show them well) and in many minerals of crystalline rocks. They are exceedingly various in form, being branching, curved, oval, or spherical, and sometimes assuming as negative crystals a geometric form, like that characteristic of the mineral in which they occur, as cubic in rock-salt and hexagonal in quartz. They also vary greatly in size. Occasionally in quartz, sapphire, and other minerals, large cavities are readily observable with the naked eye. But they may be traced with high magnifying powers down to less than $\frac{1}{10000}$ of an inch in diameter. Their proportion in any one crystal ranges within such wide limits, that whereas in some crystals of quartz few may be observed, in others they are so minute and abundant that many millions must be contained in a cubic inch. The fluid present is usually water, frequently with saline solutions, particularly chloride of sodium or of potash, or sulphates of potash, soda, or lime. Carbon-dioxide may be present in the water; sometimes the cavities are partially occupied with it in liquid form, and the two fluids, as originally observed by Brewster, may be seen in the same cavity unmingled, the carbon-dioxide remaining as a freely moving globule within the carbonated water. Cubic crystals of chloride of sodium may be occasionally observed in the fluid, which must in such cases be a saturated solution of this salt (Fig. 11, lowest figure in Column A). Usually each cavity contains a small globule or bubble, sometimes stationary, sometimes movable from one side or end of the cavity to the other, as the specimen is turned. With a high magnifying power, the minuter bubbles may be observed to be in motion, sometimes slowly pulsating from side to side, or rapidly vibrating like a living organism. The cause of this trepidation, which resembles the so-called "Brownian movements," has been plausibly explained by the incessant interchange of the molecules from the liquid to the vaporous condition along the surface where vapors and liquid meet—an interchange which, though not visible on the large bubbles, makes itself apparent in the minute examples, of which the dimensions are comparable to those of the intermolecular spaces.[83] The bubble may be made to disappear by the application of heat.

Fig. 11.—Cavities in Crystals, highly magnified; A, Liquid Inclusions; B, Glass Inclusions; C, Cavities showing the devitrification of the original glass by the appearance of crystals, etc., until in the lowest figure a stony or lithoid product is formed.

With regard to the origin of the bubble, Sorby pointed out that it can be imitated in artificial crystals, in which he explained its existence by diminution of volume of the liquid owing to a lowering of temperature after its inclosure. By a series of experiments he ascertained the rate of expansion of water and saline solutions up to a temperature of 200° C. (392° Fahr.), and calculated from them the temperature at which the liquid in crystals would entirely fill its

[83] Charbonelle and Thirion, Rev. Quest. Scientif. vii. (1880) 43. On the critical point of water, etc., in these cavities see Hartley, Journ. Chem. Soc. ser. 3, vol. ii. p. 241. Pop. Sci. Rev. new ser. i. p. 119.

inclosing cavities. Thus, in the nepheline of the ejected blocks of Monte Somma, he found that the relative size of the vacuities was about ·28 of the fluid, and assuming the pressure under which the crystals were formed to have been not much greater than sufficient to counteract the elastic force of the vapor, he concluded that the nepheline may have been formed at a temperature of about 340° C. (644° Fahr.), or a very dull red heat, only just visible in the dark. He estimated also from the fluid cavities in the quartz of granite that this rock has probably consolidated at somewhat similar temperatures, under a pressure sometimes equal to that of 76,000 feet of rock.[84] Zirkel, however, has pointed out that even in contiguous cavities, where there is no evidence of leakage through fine fissures, the relative size of the vacuole varies within very wide limits, and in such a manner as to indicate no relation whatever to the dimensions of the inclosing cavities. Had the vacuole been due merely to the contraction of the liquid on cooling, it ought to have always been proportionate to the size of the cavity.[85]

MM. De la Vallée Poussin and Renard, attacking the question from another side, measured the relative dimensions of the vesicle and of its inclosed water and cube of rock-salt, as contained in the quartziferous diorite of Quenast in Belgium. The temperature at which the ascertained volume of water in the cavity would dissolve its salt was found by calculation to be 307° C. (520° Fahr.). But as the law of the solubility of common salt has not been experimentally determined for high temperatures, this figure can only be accepted provisionally, though other

[84] Sorby, Q. J. Geol. Soc. xiv. pp. 480, 493. [85] "Mik. Beschaff." p. 46.

considerations go to indicate that it is probably not far from the truth. Assuming then that this was the temperature at which the vesicle was formed, these authors proceed to determine the pressure necessary to prevent the complete vaporization of the water at that temperature, and obtain, as the result, a pressure of 87 atmospheres, equal to 84 tons per square foot of surface.[86] That many rocks were formed under great pressure is well shown by the liquid carbon-dioxide in the pores of their crystals.

Although, in almost all cases, the liquid inclusions are to be referred to the conditions under which the mineral crystallized out of the original magma, they may be exceptionally developed long subsequently, either in one of the original minerals during decomposition, or in a mineral of secondary origin, such as quartz of subsequent introduction.[87]

Liquid inclusions may be dispersed at random through a crystal, or as in the quartz of granite, gathered in intersecting planes (which look like fine fissures and which may sometimes have become real fissures, owing to the line of weakness caused by the crowding of the cavities), or disposed regularly in reference to the contour of the crystal. In the last case they are sometimes confined to the centre, sometimes arranged in zones along the lines of growth of the crystal.[88] They are specially conspicuous in the quartz

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[86] "Mémoire sur les Roches dites Plutoniennes de la Belgique," De la Vallée Poussin and A. Renard. Acad. Roy. Belg. 1876, p. 41. See also Ward, Q. J. Geol. Soc. xxxi. p. 568, who believed that the granites of Cumberland consolidated at a maximum depth of 22,000 to 30,000 feet.

[87] See Whitman Cross on the development of liquid inclusions in plagioclase during the decomposition of the gneiss of Brittany. Tschermak's Min. Mittheil. 1880, p. 369; also G. F. Becker, "Geology of Comstock Lode." U. S. Geol. Surv. 1882, p. 371.

[88] The way in which vesicles, inclosed crystals, etc., are grouped along the zones of growth of crystals is illustrated in Fig. 12.

of granite and other massive rocks, as well as of gneiss and mica-schist; also in felspars, topaz, beryl, augite, nepheline, olivine, leucite and other minerals.

γ. Inclusions of glass or of some lithoid substance.—In many rocks which have consolidated from fusion, the component crystals contain globules or irregularly shaped inclosures of a vitreous nature (Fig. 11, Column B). These inclosures are analogous to the fluid-inclusions just described. They are portions of the original glassy magma out of which the minerals of the rock crystallized, as portions of the mother-liquor are inclosed in artificially formed crystals of common salt. That magma is in reality a liquid at high temperatures, though at ordinary temperatures it becomes a solid. At first, these glass-vesicles may be confounded with the true liquid-cavities, which in some respects they closely resemble. But they may be distinguished by the immobility of their bubbles, of which several are sometimes present in the same cavity; by the absence of any diminution of the bubbles when heat is applied; by the elongated shape of many of the bubbles; by the occasional extrusion of a bubble almost beyond the walls of the vesicle; by the usual pale greenish or brownish tint of the substance filling the vesicle, and its identity with that forming the surrounding base or ground-mass in which the crystals are imbedded; and by the complete passivity of the substance in polarized light (see p. 169).

Glass inclusions occur abundantly in some minerals, aggregated in the centre of a crystal or ranged along its zones of growth with singular regularity. They appear in felspars, quartz, leucite, and other crystalline ingredients of volcanic rocks, and of course prove that in such positions these minerals, even the refractory quartz, have undoubtedly crystallized out of molten solutions.

In inclusions of a truly vitreous nature, traces of devitrification may not infrequently be seen. In particular, microscopic crystallites (p. 205) make their appearance, like those in the ground-mass of the rock. Sometimes the inclusions, like the general ground-mass, have an entirely stony character (Fig. 11, C). This may be well observed in those which have not been entirely separated from the surrounding ground-mass, but are connected with it by a narrow neck at the periphery of the inclosing crystal. In some granites and in elvans, the quartz by irregular contraction, while still in a plastic state, appears to have drawn into its substance portions of the surrounding already lithoid base;[89] but this appearance may sometimes be due to irregular corrosion of the crystals by the magma.[90]

δ. Crystals and crystalline bodies.—Many com-

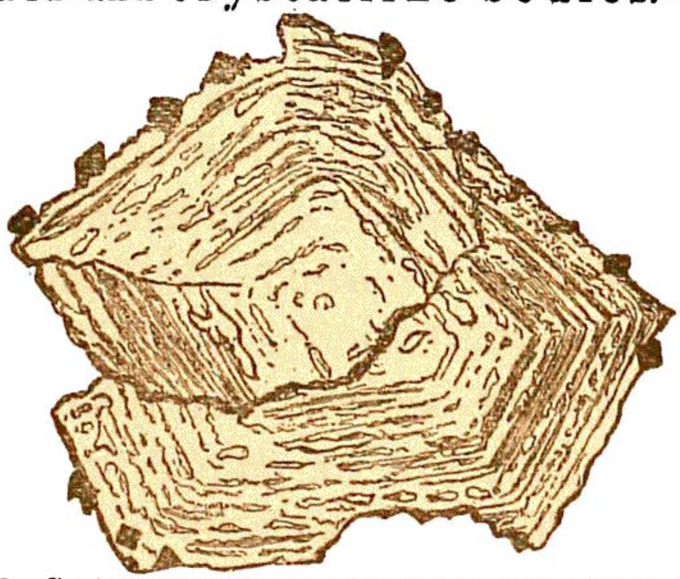

Fig. 12.—Section of a fractured and corroded Augite crystal from a dike, Crawfordjohn, Lanarkshire (magnified), showing lines of growth with vesicles and magnetite crystals.

ponent minerals of rocks contain other minerals (Fig. 12). These occur sometimes as perfect crystals, more usually

[89] J. A. Phillips, Q. J. Geol. Soc. xxxi. p. 338.
[90] Fouqué and Michel-Lévy, "Min. Micrograph."

as what are termed microlites (p. 205). Like the glass-inclusions, they tend to range themselves in lines along the successive zones of growth in the inclosing mineral. Microlites are of frequent occurrence in leucite, garnet, augite, hornblende, calcite, fluorite, etc. From the fact that microlites of the easily fusible augite are, in the Vesuvian lavas, inclosed within the extremely refractory leucite, it was supposed that the relative order of fusibility is not always followed in the microlites and enveloping crystals. But this has been satisfactorily explained by Fouqué and Michel-Lévy, who have shown experimentally that leucite, when crystallizing from fusion, tends to catch up inclusions of the surrounding glass, which, should the glass be pyroxenic, may assume the form of augite.[91]

ε. Filaments, streaks, patches, discolorations.—Besides the inclosures already enumerated, crystals likewise frequently inclose irregular portions of mineral matter, due to alteration of the original substance of the minerals or rocks. Thus tufts and vermicular aggregates of certain green ferruginous silicates are of common occurrence among the crystals and cavities of old pyroxenic volcanic rocks. Orthoclase crystals are often mottled with patches of a granular nature, due to partial conversion of the mineral into kaolin. The magnetite, so frequently inclosed within minerals, is abundantly oxidized, and has given rise to brown and yellow patches and discolorations. Care must be taken not to confound these results of infiltrating water with the original characters of a rock. Practice will give the student confidence in distinguishing them, if he familiarizes his eye with decomposition products by studying slices of weathered minerals and of the weathered parts of rocks.

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[91] "Synthèse des Minéraux," 1882, p. 155.

B. GLASS.—Even to the unassisted eye, many volcanic rocks consist obviously in whole or in great measure of glass.[92] This substance in mass is usually black or dark green, but when examined in thin sections under the microscope, it presents for the most part a pale brown tint, or is nearly colorless. In its purest condition, it is quite structureless, that is, it contains no crystals, crystallites, or other distinguishable individualized bodies. But even in this state it may sometimes be observed to be marked by clot-like patches or streaks of darker and lighter tint, arranged in lines or eddy-like curves, indicative of the flow of the original fluid mass. Rotated in the dark field of crossed Nicol-prisms, such a natural glass remains dark, as, unless where it has undergone internal stresses, it is perfectly inert in polarized light. Being thus *isotropic*, it may readily be distinguished from any inclosed crystals which, acting on the light, are *anisotropic* (p. 169). Perfectly homogeneous structureless glass, without inclosures of any kind, occurs for the most part only in limited patches, even in the most thoroughly vitreous rocks. Originally the structure of all glassy rocks, at the time of most complete fusion, may have been that of perfectly unindividualized glass. But as these masses tended toward a solid form, devitrification of their glass set in. Many forms of incipient or imperfect crystallization, as well as perfect crystals, were developed in the still fluid and moving mass, and, together with crystals of earlier growth, were arranged in the direction of motion. Devitrification has in frequent examples proceeded so far that no trace remains of any actual glass.[93]

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[92] See E. Cohen on glassy Rocks. Neues Jahrb. 1880 (ii.), p. 23.

[93] Consult a paper on the microscopic character of devitrified glass and some analogous rock-structures, by D. Herman and F. Rutley. Proc. Roy. Soc. 1885, p. 87.

C. CRYSTALLITES AND MICROLITES.[94] — Under these names may be included minute inorganic bodies possessing a more or less definite form, but generally without the geometrical characters of crystals. They occur most commonly in rocks which have been formed from igneous fusion, but are found also in others which have resulted from, or have been altered by, aqueous solutions. They seem to be early or peculiar forms of crystallization. They are abundantly developed in artificial slags, and appear in many modern and ancient vitreous rocks, but the conditions under which they are produced are not yet well understood.[95]

Crystallites are distinguished by remaining isotropic in polarized light. The simplest are extremely minute drop-like bodies or *globulites*, sometimes crowded confusedly through the glass, giving it a dull or somewhat granular character, while in other cases they are arranged in lines or groups. Gradations can be traced from spherical or spheroidal globulites into other forms more elliptical in shape, but still having a rounded outline and sometimes sharp ends (*longulites*). There does not appear to be any essential distinction, save in degree of development, between these forms and the long rod-like or needle-shaped bodies which have been termed *belonites*. Existing sometimes as mere simple needles or rods, these more elongated crystallites may be traced into more complex forms, curved or coiled, at one

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[94] The word *crystallite* was first used by Sir James Hall to denote the lithoid substance obtained by him after fusing and then slowly cooling various "whinstones" (diabases, etc.). Since its revival in lithology it has been applied to the minuter bodies above described. The student should consult Vogelsang's "Philosophie der Geologie," p. 139; "Krystalliten," Bonn, 8vo, 1875; also his descriptions in Archives Néerlandaises, v. 1870, vi. 1871. Sorby, Brit. Assoc. 1880.

[95] They are well exhibited also in ordinary blow-pipe beads. See Sorby, Brit. Assoc. 1880, or Geol. Mag. 1880, p. 468. They have been produced experimentally in the artificial rocks fused by Messrs. Fouqué and Michel-Lévy.

time solitary, at another in groups. In most cases, crystallites are transparent and colorless, or slightly tinted, but sometimes they are black and opaque, from a coating of ferruginous oxide, or only appear so as an optical delusion from their position. Black, seemingly opaque, hair-like, twisted and curved forms, termed *trichites*, occur abundantly in obsidian.

Microlites are other incipient forms of crystallization which differ from crystallites in that they react on polarized light. They assume rod-like or needle-shaped forms, sometimes occurring singly, sometimes in aggregates, and even occasionally grouped into skeleton-crystals. They can for the most part be identified as rudimentary forms of definite minerals such as augite, hornblende, felspar, olivine, and magnetite.

Good illustrations of the general character and grouping

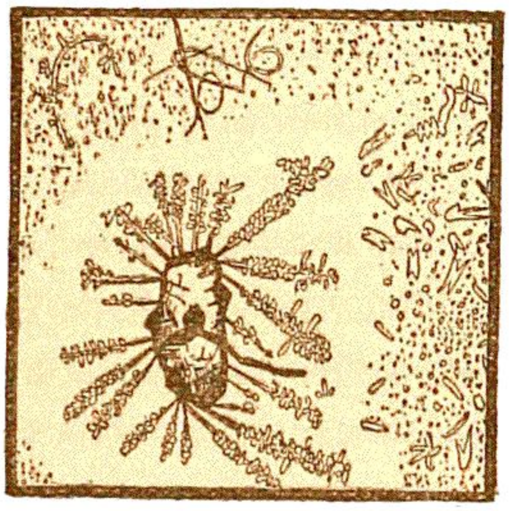

Fig. 13.—Augite Crystal surrounded by Crystallites and Microlites, from the vitreous Andesite of Eskdalemuir, magnified 800 Diameters.

Fig. 14.—Microlites of the Pitchstone of Arran, magnified 70 Diameters. (See p. 283.)

of crystallites and microlites are shown in some vitreous basalts. In Fig. 13, for example, the outer portion of the field displays crowded globulites and longulites as well as here and there a few belonites and some curved and coiled trichites. Round the rude augite crystal, these various bodies have been drawn together out of the surrounding glass. Numerous rod-like microlites diverge from the crystal, and these are more or less thickly crusted with the simpler and smaller forms.[96] In Fig. 14, the remarkably beautiful structure of an Arran pitchstone is shown; the glassy base being crowded with minute microlites of hornblende which are grouped in a fine feathery or brush-like arrangement round tapering rods. In this case, also, we see that the glassy base has been clarified round the larger individuals by the abstraction of the crowded smaller microlites. By the progressive development of crystallites, microlites, or crystals during the cooling and consolidation of a molten rock, a glass loses its vitreous character and becomes lithoid; in other words, undergoes devitrification.

The characteristic amorphous or indefinitely granular and fibrous or scaly matter, constituting the microscopic base in which the definite crystals of felsites and porphyries are imbedded (pp. 278–281), has been the subject of much discussion. Between crossed Nicol-prisms it sometimes behaves isotropically, like a glass, but in other cases allows a mottled glimmering light to pass through. It is now well understood to be a product of the devitrification of once glassy rocks wherein the crystallitic and microlitic forms can still be recognized or have been more or less effaced by subsequent alteration by infiltrating water.[97]

Every gradation in the relative abundance of crystallites may be traced. In some obsidians and other vitreous rocks, portions of the glass can be obtained with comparatively few of them; but in the same rocks we may not infrequently

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[96] Proc. Roy. Phys. Soc. Edin. v. p. 246, Fig. 5. J. J. H. Teall, Q. J. Geol. Soc. xl. p. 221, Plate xii. Fig. 2a.

[97] See Zirkel, "Mik. Beschaff." p. 280. Rosenbusch, vol. ii. p. 60.

observe adjacent parts where they have been so largely developed as to usurp the place of the original glass, and give the rock in consequence a lithoid aspect (Fig. 11, C and pp. 278–283).

D. DETRITUS.—Many rocks are composed of the detritus of pre-existing materials. In the great majority of cases this can be readily detected, even with the naked eye. But where the texture of such detrital or fragmental (clastic) rocks becomes exceedingly fine, their true nature may require elucidation with the microscope (Figs. 21, 22). An obvious distinction can be drawn between a mass of compact detritus and a crystalline or vitreous rock. The detrital materials are found to consist of various and irregularly shaped grains, with more or less of an amorphous and generally granular paste. In some cases, the grains are broken and angular, in others they are rounded or water-worn (pp. 227–228). They may consist of minerals (quartz, chert, felspars, mica, etc.), or of rocks (slate, limestone, basalt, etc.), or of the remains of plants or animals (spores of lycopods, fragments of shells, crinoids, etc.). It is evident therefore that though some of them may be crystalline, the rock of which they now form part is a non-crystalline compound. Water, with carbonate of lime or other mineral matter in solution, permeating a detrital rock, has sometimes allowed its dissolved materials to crystallize among the interstices of the detritus, thus producing a more or less distinctly crystalline structure. But the fundamentally secondary or derivative nature of the mass is not always thereby effaced.

2. *Microscopic Structures of Rocks*

We have next to consider the manner in which the foregoing microscopic elements are associated in rocks. This inquiry brings before us the minute structure or texture of rocks, and throws great light upon their origin and history.[98]

Four types of rock-structure are revealed by the microscope. A, holocrystalline; B, hemi-crystalline; C, glassy; D, clastic.

A. HOLOCRYSTALLINE, consisting entirely of crystals or crystalline individuals, whether visible to the naked eye, or requiring the aid of a microscope, imbedded in each other without any intervening amorphous substance. Rocks of this type are exemplified by granite (Figs. 15 and 29) and by other igneous rocks. But they occur also among the crystalline limestones and schists, as in statuary marble, which consists entirely of crystalline granules of calcite (Fig. 28).

According to the classification proposed by Prof. Rosenbusch the holocrystalline structure is *idiomorphic* or *panidiomorphic* when each of the component crystals has assumed its own crystallographic form, and *allotriomorphic* when it has its outlines determined by those of its neighbors. When interspaces have been left between the crystals or crystalline grains the structure is *miarolitic* or saccharoid.

The holocrystalline eruptive rocks (p. 269) are typically represented by granite, hence the term *granitoid* has been adopted to express their microscopic structure. Varieties of this structure are designated according to the relations of the component minerals. Where no one mineral greatly preponderates, but where they are all confusedly and tolerably equally distributed in individuals readily observable by the naked eye, as ordinary granite, the structure is

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[98] The first broad classification of the microscopic structure of rocks was that proposed by Zirkel, which, with slight modification, is here adopted. "Mik. Beschaff." p. 265. "Basaltgesteine," p. 88. See also Rosenbusch's suggestive paper already cited, Neues. Jahrb. 1882 (ii.), p. 1.

granitic (see *granular*, p. 177). Where a similar structure is so fine that it can only be recognized with the microscope, it has been called *microgranitic* or *euritic*. Where the minerals are grouped in small, isolated, grain-like individuals, each having its own independent crystalline structure, so that under the microscope in polarized light, the rock presents the appearance of a brilliant

Fig. 15.—Holocrystalline Structure. Granite (20 Diameters). The white portions are Quartz, the striped parts Felspar, the long, dark, finely striated stripes are Mica. (See p. 273.)

Fig. 16.—Hemi-crystalline Structure. Dolerite, consisting of a triclinic Felspar, Augite, and Magnetite in a devitrified Ground-mass (20 Diameters). The numerous narrow prisms are tricilinic Felspar; the broader monoclinic forms, slightly shaded in the drawing, are Augite; the black specks are Magnetite; the needle-shaped forms are Apatite. (See p. 294.)

mosaic, the structure has been named *granulitic* or *micro-granulitic* (*panidiomorphic granular* or *porphyric* of Rosenbusch). Where the quartz and felspar of a granitic rock have crystallized together, one within the other, the structure is *pegmatitic* (Fig. 31) where visible to the naked eye, and *micropegmatitic* (*granophyric* of Rosenbusch) where the help of a microscope is needed (Fig. 5).[99]

[99] Fouqué and Michel-Lévy, "Min. Micrograph." The micropegmatite of Michel-Lévy is the same as the structure subsequently named granophyre by Rosenbusch. Michel-Lévy, "Roches Eruptives," p. 19.

B. HEMI-CRYSTALLINE.[100]—This division probably comprehends the majority of the massive eruptive or igneous rocks. It is distinguished by the occurrence of what appears to the naked eye as a compact or finely granular ground-mass, through which more or less recognizable crystals are scattered. Examined with the microscope, this ground-mass is found to present considerable diversity (Figs. 16, 18, 32). It may be (1) wholly a glass, as in some basalts, trachytes, and other volcanic products; (2) partly devitrified through separation of peculiar little granules and needles (crystallites and microlites) which appear in a vitreous base; (3) still further devitrified, until it becomes an aggregation of such little granules, needles, and hairs, between which little or no glass-base appears (micro-crystallitic); or (4) "microfelsitic" (petrosiliceous), closely related to the two previous groups, and consisting of a nearly structureless mass, marked usually with indefinite or half-effaced granules and filaments, but behaving like a singly-refracting, amorphous body (p. 204).

In rocks belonging to this type, a *spherulitic* structure has sometimes been produced by the appearance of globular bodies composed of a crystalline internally radiating substance, sometimes with concentric shells of amorphous material. In many cases, spherulites are only recognizable with the microscope, when they each present a black cross between crossed Nicol-prisms, and thereby characteristically reveal the *microspherulitic* structure (Figs. 7 and 17).[101]

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[100] For this structure the term "mixed" has been proposed, as being a mixture of the crystalline and amorphous (glassy) structures. It has been designated by Fouqué and Michel-Lévy "trachytoid," as being typically developed among the trachytes (postea, p. 288). It is called "hypocrystalline" by Rosenbusch.

[101] Fouqué and Michel-Lévy, "Min. Micrograph." Some remarkably beautiful examples of microspherulitic structure occur in the quartz-porphyries that traverse the lower Cambrian tuffs at St. David's. Q. J. Geol. Soc. xxxix. p. 313.

The term ophitic is applied to a structure in which one mineral after crystallizing has been inclosed within another during the consolidation of an igneous rock (Fig. 18). It is abundant in many dolerites and diabases where some bisilicate such as augite serves as a matrix in which the felspars and other crystals are inclosed. The name is derived from the so-called "ophites" of the Pyrenees.[102]

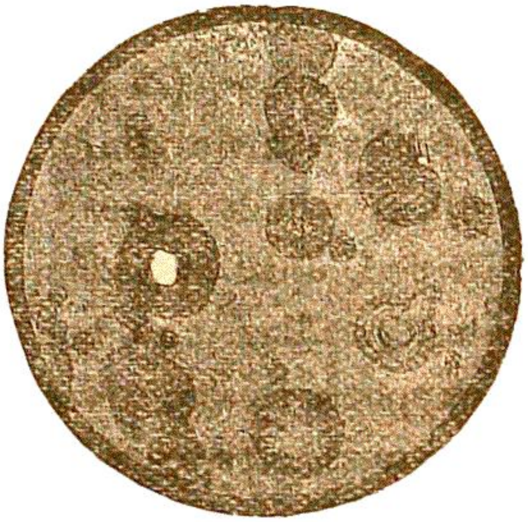

Fig. 17.—Spherulitic Structure. Pitchstone, Raasay (magnified).

Fig. 18.—Ophitic Structure. Dolerite, Skye (magnified).

C. GLASSY.—Composed of a volcanic glass such as has already been described. It seldom happens, however, that rocks which seem to the eye to be tolerably homogeneous glass do not contain abundant crystallites and minute crystals. Hence truly vitreous rocks tend to graduate into the second or hemi-crystalline type. This gradation and the abundant traces of a devitrified base or magma between the crystals of a vast number of eruptive rocks, lead to the belief that the glassy type was the original condition of most if not all of these rocks. Erupted as molten masses, their mobility would depend upon the fluidity of the glass. Yet even while still deep within the earth's crust, some of their constituent minerals (felspars, leucite, magnetite, etc.) were

[102] These rocks (diabases) have been critically studied by J. Kühn, Zeitsch. Deutsch. Geol. Ges. xxxiii. (1881) 372.

often already crystallized, and suffered fracture and corrosion by subsequent action of the inclosing magma. This is well shown by what is termed the *flow-structure* or *fluxion-structure.* Crystals and crystallites are ranged in current-like lines, with their long axes in the direction of these lines. Where a large older crystal occurs, the train of minuter individuals is found to sweep round it and to reunite on the further side, or to be diverted in an eddy-like course (Fig. 19). So thoroughly is this arrangement characteristic of the motion of a somewhat viscid liquid, that there cannot be any doubt that such was the condition

Fig. 19.—Flow-structure in Obsidian. (20 Diameters).

Fig. 20.—Perlitic Structure. Felsitic glass. Mull (magnified).

of these masses before their consolidation. The flow-structure may be detected in many eruptive rocks, from thoroughly vitreous compounds like obsidian, on the one hand, to completely crystalline masses like some dolerites, on the other. It occurs not only in what are usually regarded as volcanic rocks, but also in plutonic or deep-seated masses which, there is reason to believe, consolidated beneath the surface, as for instance in the Bode vein of the Harz, among quartz-porphyries associated with granites in Aberdeenshire, and in felsite dikes and bosses in the Shetlands, Skye, central Scotland, and County Waterford.

The structure, therefore, cannot be regarded as certainly indicating that the rock in which it is found ever flowed out at the surface as lava.

Some glassy rocks, in cooling and consolidating, have had spherulites developed in them (Fig. 17); also by contraction the system of reticulated and spiral cracks known as *perlitic* structure (p. 180 and Figs. 9 and 20).

The final stiffening of a vitreous mass into solid stone has resulted (1st) from mere solidification of the glass: this is well seen at the edge of dikes and intrusive sheets of different basalt-rocks, where the igneous mass, having been suddenly congealed along its line of contact with the surrounding rocks, remains there in the condition of glass, though only an inch further inward from the edge the vitreous magma has disappeared, as represented in Fig. 287; (2d) from the devitrification of the glass by the abundant development of microfelsitic granules and filaments, as in quartz-porphyry, or of crystallites, microlites and crystals, as in such glassy rocks as obsidian and tachylite; or (3d) from the complete crystallization of the whole of the original glassy base, as may be observed in some dolerites.

D. Clastic.—Composed of detrital materials, such as have been already described (p. 183 and Fig. 21). Where these materials consist of grains of quartz-sand, they withstand almost any subsequent change, and hence can be recognized even among a highly metamorphosed series of rocks. Quartzite from such a series can sometimes be scarcely distinguished under the microscope from unaltered quartzose sandstone. Where the detritus has resulted from the destruction of aluminous or magnesian silicates, it is more susceptible of alteration. Hence it can be traced in regions of local metamorphism, becoming more and more crystalline, until the rocks formed of or containing it pass into true crystalline schists.

Detritus derived from the comminution or decay of organic remains presents very different and characteristic structures[103] (Fig. 22). Sometimes it is of a siliceous nature, as where it has been derived from diatoms and radiolarians. But most of the organically-derived detrital rocks are calcareous, formed from the remains of foraminifera, corals, echinoderms, polyzoa, cirripeds, annelids, mollusks, crustacea and other invertebrates, with occasional traces of fishes

Fig. 21.—Clastic Structure, of Inorganic origin—Section of a Piece of Greywacke. (10 Diameters. See p. 232.)

Fig. 22.—Clastic Structure, of Organic Origin—Structure of Chalk (Sorby). Magnified 100 Diameters. (See p. 246.)

or even of higher vertebrates. Distinct differences of microscopic structure can be detected in the hard parts of some of the living representatives of these forms, and similar differences have been detected in beds of limestone of all ages. Mr. Sorby, in the paper cited below, has shown how characteristic and persistent are some of these distinctions, and how they may be made to indicate the origin of the rock in which they occur. There is an important difference between the two forms in which carbonate of lime is made

[103] The student who would further investigate this subject, will find a suggestive and luminous essay upon it by Mr. Sorby in his Presidential Address to the Geological Society, Quart. Journ. Geol. Soc. 1879.

use of by invertebrate animals; aragonite being much less durable than calcite (pp. 141, 244). Hence while shells of gasteropods, many lamellibranchs, corals and other organisms, formed largely or wholly of aragonite, crumble down into mere amorphous mud, pass into crystalline calcite, or disappear, the fragments of those consisting of calcite may remain quite recognizable.

It is evident, therefore, that the absence of all trace of organic structure in a limestone need not invalidate an inference from other evidence that the rock has been formed from the remains of organisms. The calcareous organic débris of a sea-bottom may be disintegrated, and reduced to amorphous detritus, by the mechanical action of waves and currents, by the solvent chemical action of the water, by the decay of the binding material, such as the organic matter of shells, or by being swallowed and digested by other animals (postea, p. 243).[104]

Moreover, in clastic calcareous rocks, owing to their liability to alteration by infiltrating water, there is a tendency to acquire an internal crystalline texture (p. 621). At the time of formation, little empty spaces lie between the component granules and fragments, and according to Mr. Sorby these interspaces may amount to about a quarter of the whole mass of the rock. They have very commonly been filled up by calcite introduced in solution. This infiltrated calcite acquires a crystalline structure, like that of ordinary mineral-veins. But the original component organic granules also themselves become crystalline, and, save in so far as their external contour may reveal their original

[104] Sorby, Presidential Address, Q. J. Geol. Soc. 1879. G. Rose, Abhandl. Acad. Berlin, 1858; Gümbel, Zeitsch. Deutsch. Geol. Gesellsch. 1884, p. 386. Cornish and Kendall, Geol. Mag. 1888, p. 66.

organic source, they cannot be distinguished from mere mineral-grains. In this way, a cycle of geological change is completed. The calcium-carbonate originally dissolved out of rocks by infiltrating water, and carried into the sea, is secreted from the oceanic waters by corals, foraminifera, echinoderms, mollusks and other invertebrates. The remains of these creatures collected on the sea-bottom slowly accumulate into beds of detritus, which in after times are upheaved into land. Water once more percolating through the calcareous mass, gradually imparts to it a crystalline structure, and eventually all trace of organic forms may be effaced. But at the same time, the rock, once exposed to meteoric influences, is attacked by carbonated water, its molecules are carried in solution into the sea, where they will again be built up into the framework of marine organisms.

E. Alteration of Rocks by Meteoric Water.—An important revelation of the microscope is the extent to which rocks suffer from the influence of infiltrating water. The nature of some of these changes is described in subsequent pages. (Book III. Part. II. Sect. ii. § 2.) It may be sufficient to note here a few of the more obvious proofs of alteration. Threads and kernels of calcite running through an eruptive rock, such as diabase, dolerite, or andesite, are a good index of internal decomposition. They usually point to the decay of some lime-bearing mineral in the rock. Some other minerals are likewise frequent signs of alteration, such as serpentine (often resulting from the alteration of olivine, Figs. 33, 34), chlorite, epidote, limonite, chalcedony, etc. In many cases, however, the decomposition products are so indefinite in form and so minute in quantity as not to permit of their being satisfactorily referred to any known species of mineral. For these indeterminate, but frequently abundant substances, the following short names were proposed by Vogelsang to save periphrasis, until the true nature of the substance is ascertained. *Viridite*—green transparent or translucent patches, often in scaly or fibrous aggregations, of common occurrence in more or less decomposed rocks containing hornblende, augite, or olivine: probably in many cases serpentine, in others chlorite or delessite. *Ferrite*—yellowish, reddish, or brownish amorphous substances, probably consisting of peroxide of iron, either hydrous or anhydrous, but not certainly referable to any mineral, though sometimes pseudomorphous after ferruginous minerals. *Opacite*—black, opaque grains and scales of amorphous earthy matter, which may in different cases be magnetite, or some other metallic oxide, earthy silicates, graphite, etc.[105]

§ vi. Classification of Rocks

It is evident that Lithology may be approached from two very different sides. We may, on the one hand, regard rocks chiefly as so many masses of mineral matter, presenting great variety of chemical composition and marvellous diversity of microscopic structure. Or, on the other hand, passing from the details of their chemical and mineralogical characters, we may look at them rather as the records of ancient terrestrial changes. In the former aspect, they present for consideration problems of the highest interest in inorganic chemistry and mineralogy; in the latter view, they invite attention to the great geological revolutions through which the planet has passed. It is evident, therefore, that

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[105] Vogelsang, Z. Deutsch. Geol. Ges. xxiv. (1872), p. 529. Zirkel, Geol. Expl. 40th Parallel, vol. vi. p. 12.

two distinct systems of classification may be followed, the one based on chemical and mineralogical, the other on geological considerations.

From a chemical point of view, rocks may be grouped according to their composition; as Oxides, exemplified by formations of quartz, hæmatite, or magnetite; Carbonates, including the limestones and clay-ironstones; Silicates, embracing the vast majority of rocks, whether composed of a single mineral, or of more than one; Phosphates, such as guano and the older bone-beds and coprolitic deposits. A classification of this kind, however, pays no regard to the mode of origin or conditions of occurrence of the rocks, and is not well suited for the purposes of the geologist.[106]

From the mineralogical side, rocks may be classified with reference to their prevailing mineral constituent. Thus such subdivisions as Calcareous rocks, Quartzose rocks, Orthoclase rocks, Plagioclase rocks, Pyroxenic rocks, Hornblendic rocks, etc., may be adopted; but these terms are hardly less objectionable to the geologist, and are in fact suited rather for the arrangement of hand-specimens in a museum, than for the investigation of rocks *in situ*.

From the standpoint of geological inquiry, rocks have been classified according to their mode of origin. In one system they are arranged under three great divisions: 1st, *Igneous*, embracing all which have been erupted from the heated interior of the earth; 2d, *Aqueous* or *Sedimentary*, including all which have been laid down as mechanical or chemical deposits from water or air, and all which have resulted from the growth and decay of plants or animals; 3d, *Metamorphic*, those which have undergone subsequent

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[106] The eruptive rocks are susceptible of a convenient, though not strictly accurate, chemical classification into *acid*, *intermediate* and *basic* (see p. 273).

change within the crust of the earth, whereby their original character has been so modified as to be sometimes quite indeterminable. Another geological arrangement is based upon the general structure of the rocks, and consists of two divisions: 1st, *Stratified*, embracing all the aqueous and sedimentary, with part of the less altered metamorphic rocks; 2d, *Unstratified*, nearly conterminous with the term igneous, since it includes all the eruptive rocks. Further subdivisions of this series have been proposed according to differences of structure or texture, as *porphyritic*, *granitic*, etc. These geological subdivisions, however, ignore the chemical and mineralogical characters of the rocks, and are based on deductions which may not always be sound. Thus, rocks may be included in the igneous series which further research may show not to be of igneous origin; others may be classed as metamorphic, regarding the true origin of which there may be considerable uncertainty.

A further system of classification, based upon relative age, has been applied to the arrangement of the eruptive rocks, those masses which were erupted prior to Secondary time being classed as "older," and those of Tertiary and later date as "younger." This system has been elaborated in great detail by Michel-Lévy, who maintains that the same types have been reproduced nearly in the same order in the two series, though basic rocks, often with vitreous characters, rather predominate in the later.[107] It must, indeed, be

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[107] See on this subject, J. D. Dana, Amer. J. Sci. xvi. 1878, p. 336. Michel-Lévy, Bull. Soc. Géol. France, 3d ser. iii. (1874), p. 199; vi. p. 173. Ann. des Mines, viii. (1875) "Roches Eruptives," 1889. Fouqué and Michel-Lévy, "Mineralogie Microgr." p. 150. Rosenbusch, "Mik. Physiog." ii. Reyer, "Physik der Eruptionen," 1877, part iii. opposes the adoption of relative age as a basis of classification. On the classification of compound silicated rocks, see Vogelsang, Z. Deutsch. Geol. Ges. xxiv. p. 507; and for an incisive criticism of a too merely mineralogical classification, Lossen, op. cit. xxiv. p. 782. Consult also O. Lang, "Ueber die Individualität der Gesteine" in Tschermak's Min. Mittheil. vol. xi. part 6 (1890), p. 467.

admitted that certain broad distinctions between the older and the later eruptive rocks have been well ascertained, and appear to hold generally over the world. Among these distinctions may be mentioned as more characteristic of the Palæozoic rocks the presence of microcline, turbid orthoclase in Carlsbad twins, muscovite, enstatite, bronzite, diallage, tourmaline, anatase, rutile, cordierite, and in the younger rocks the presence of sanidine, tridymite, leucite, nosean, hauyne, and zeolites. Even where the same mineral occurs in both the older and newer series, it often presents a somewhat different aspect in each, as in the case of the plagioclase and augite, which in the younger series are distinguished by the occurrence in them of vitreous and gaseous inclusions which are rare or absent in those of the older series.[108] Throughout the younger eruptive rocks, the vitreous condition is much more frequent and perfectly developed than in the older group, where, on the other hand, the granitic structure is characteristically displayed. Still, to these rules so many exceptions occur that it may be doubted whether enough of positively ascertained data have been collected regarding the relative ages of eruptive rocks to warrant the adoption of any classification upon a chronological basis. There can be no doubt that, making due allowance for the alterations arising from permeation by meteoric water, there is no essential difference between some types of volcanic rock in Palæozoic and in recent times. The Carboniferous basalts and trachytes of Scotland, for example, present the closest resemblance to those of Tertiary age.[109]

Though no classification which can at present be pro-

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[108] See J. Murray and A. Renard, Proc. Roy. Soc. Edin. xi. p. 669.
[109] See Nature, iii. (1871), p. 306.

posed is wholly satisfactory, one which shall do least violence, at once to geological and mineralogical relationships, is to be preferred. The arrangement which has met with the most general acceptance is threefold. 1st, Sedimentary Rocks, including first the rocks which have resulted from the accumulation of detritus, either inorganic or organic, under water or on land, and secondly those which have been deposited from aqueous solution. The former are mechanical, the latter chemical accumulations; but they have often been deposited together. Certain rocks of mechanical origin, such as detrital limestones, may by subsequent alteration be converted into materials that cannot be distinguished from others of true chemical origin. Hence the whole series is intimately linked together. 2d, Massive, Eruptive, or Intrusive Rocks, embracing all those which have solidified from fusion within the earth's crust, or have been erupted as lava to the surface. 3d, Schistose Rocks, and their accompaniments, including the so-called Metamorphic rocks which have reached their present condition as a consequence of the alteration sometimes of sedimentary, sometimes of igneous rocks. This group graduates into the two others, but it contains some distinctive masses, the origin of which is still involved in doubt.

It must be kept in view that in this proposed system of classification, and in the following detailed description of rocks, many questions regarding the origin and decomposition of these mineral masses must necessarily be alluded to. The student, however, will find these questions discussed in later pages, and will probably recognize a distinct advantage in this unavoidable preliminary reference to them in connection with the rocks by which they are suggested.

§ vii. A Description of the more Important Rocks of the Earth's Crust

Full details regarding the composition, microscopic structure, and other characters of rocks must be sought in such general treatises and special memoirs as those already cited (pp. 160, 172, 193). The purposes of the present text-book will be served by a succinct account of the more common or important rocks which enter into the composition of the crust of the earth.

I. Sedimentary

A. Fragmental (Clastic)

This great series embraces all rocks of a secondary or derivative origin; in other words, all formed of fragmentary materials which have previously existed on or beneath the surface of the earth in another form, and the accumulation and consolidation of which gives rise to new compounds. Some of these materials have been produced by the mechanical action of wind, as in the sand-hills of sea-coasts and inland deserts (Æolian rocks); others by the operation of moving water, as the gravel, sand and mud of shores and river-beds (Aqueous sedimentary rocks); others by the accumulation of the entire or fragmentary remains of once living plants and animals (Organically-formed rocks); while yet another series has arisen from the gathering together of the loose débris thrown out by volcanoes (Volcanic tuffs). It is evident that in dealing with these various detrital formations, the degree of consolidation is of secondary importance. The soft sand and mud of a modern lake-bottom differ in no essential respect from ancient lacustrine strata, and may tell their geological story equally well. No line is to be drawn between what is popularly termed rock and the loose, as yet uncompacted, débris out of which solid rocks may eventually be formed. Hence in the following arrangement, the modern and the ancient, being one in structure and mode of formation, are classed together.

It will be observed that, in several directions, we are led by the fragmental rocks to crystalline stratified deposits, some of which have been deposited from chemical solution, while others have resulted from the gradual conversion of a detrital into a crystalline structure. Both series of deposits are accumulated simultaneously and are often interstratified. Calcareous rocks formed of organic remains (p. 243) exhibit very clearly this gradual internal change, which more or less effaces their detrital origin, and gives them such a crystalline character as to entitle them to be ranked among the crystalline limestones.

1. **Gravel and Sand Rocks** (Psammites)

As the deposits included in this subdivision are produced by the disintegration and removal of rocks by the action of the atmosphere, rain, rivers, frost, the sea, and other superficial agencies, they are mere mechanical accumulations, and necessarily vary indefinitely in composition, according to the nature of the sources from which they are derived. As a rule, they consist of the detritus of siliceous rocks, these being among the most durable materials. Quartz, in particular, enters largely into the composition of sandy and gravelly detritus. Fragmentary materials tend to group themselves according to their size and relative density. Hence they are apt to occur in layers, and to show the characteristic *stratified* arrangement of *sedimentary* rocks. They may inclose the remains of any plants or animals entombed on the same sea-floor, river-bed, or lake-bottom.

In the majority of these rocks, their general mineral composition is obvious to the naked eye. But the application of the microscope to their investigation has thrown considerable light upon their composition, formation, and subsequent mutations. Their component materials are thus ascertained to be divisible into—1st, derived fragments, of which the most abundant are quartz, after which come felspar, mica, iron-ores, zircon, rutile, apatite, tourmaline, garnet, sphene, augite, hornblende, fragments of various rocks, and clastic dust; 2d, constituents which have been deposited between the particles, and which in many cases serve as the cementing material of the rock. Among the more important of these are silicic acid in the form of quartz, chalcedony and opal; carbonates of lime, iron or magnesia; hæmatite, limonite; pyrite and glauconite.[110]

Cliff-Debris, Moraine Stuff—angular rubbish disengaged by frost and ordinary atmospheric waste from cliffs, crags, and steep slopes. It slides down the declivities of hilly regions, and accumulates at their base, until washed away by rain or by brooks. It forms talus-slopes of as much as 40°, though for short distances, if the blocks are large, the general angle of slope may be much steeper. It naturally depends for its composition upon the nature of the solid rocks from which it is derived. Where cliff-débris falls upon and is borne along by glaciers it is called "Moraine-stuff," which may be deposited near its source, or may be transported for many miles on the surface of the ice (p. 714).

Perched Blocks, Erratic Blocks—large masses of rock, often as big as a house, which have been transported by glacier-ice, and have been lodged in a prominent position in glacier valleys or have been scattered over hills and plains. An examination of their mineralogical character leads to the identification of their source, and, consequently, to the path taken by the transporting ice. (See Book III. Part II. Section ii. § 5.)

Rain-wash—a loam or earth which accumulates on the lower parts of slopes or at their base, and is due to the gradual descent of the finer particles of disintegrated rocks by the transporting action of rain. Brick-earth is the name given in the southeast of England to thick masses of such loam, which is extensively used for making bricks.

Soil—the product of the subaerial decomposition of rocks and of the decay of plants and animals. Primarily the character of the soil is determined by that of the subsoil, of which indeed it is merely a further disintegration. Ac-

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[110] G. Klemm, Zeitsch. Deutsch. Geol. Ges. xxxiv. (1882), p. 771. H. C. Sorby, Quart. Journ. Geol. Soc. xxxvi. (1880). J. A. Phillips, op. cit. xxxvii. (1881), p. 6

cording to the nature of the rock underneath, a soil may vary from a stiff clay, through various clayey and sandy loams, to mere sand. The formation of soil is treated of in Book III. Part II. Section ii. § 1.

Subsoil—the broken-up part of the rocks immediately under the soil. Its character, of course, is determined by that of the rock out of which it is formed by subaerial disintegration. (Book III. Part II. Section ii. § 1.)

Blown Sand—loose sand usually arranged in lines of dunes, fronting a sandy beach or in the arid interior of a continent. It is piled up by the driving action of wind. (Book III. Part II. Section i.) It varies in composition, being sometimes entirely siliceous, as upon shores where siliceous rocks are exposed; sometimes calcareous, where derived from triturated shells, nullipores, or other calcareous organisms. The minute grains from long-continued mutual friction assume remarkably rounded and polished forms. Layers of finer and coarser particles often alternate, as in water-formed sandstone. On many coast-lines in Europe, grasses and other plants bind the surface of the shifting sand. These layers of vegetation are apt to be covered by fresh encroachments of the loose material, and then by their decay to give rise to dark peaty seams in the sand. Calcareous blown sand is compacted into hard stone by the action of rain-water, which alternately dissolves a little of the lime, and re-deposits it on evaporation as a thin crust cementing the grains of sand together. In the Bahamas and Bermudas, extensive masses of calcareous blown sand have been cemented in this way into solid stone, which weathers into picturesque crags and caves like a limestone of older geological date.[111] At Newquay, Cornwall, blown sand has been by the decay of abundant land-shells solidified into a material capable of being used as a building-stone.

River-sand, Sea-sand.—When the rounded water-worn detritus is finer than that to which the term gravel would be applied, it is called sand, though there is obviously no line to be drawn between the two kinds of deposit, which necessarily graduate into each other. The particles of sand range down to such minute forms as can only be distinctly dis-

[111] For interesting accounts of the Æolian deposits of the Bahama and Bermudas, see Nelson, Q. J. Geol. Soc. ix. p. 200, Sir Wyville Thomson's "Atlantic," vol. i.; also J. J. Rein, Senckenb. Nat. Gesellsch. Bericht. 1869–70, p. 140, 1872–73, p. 131. On the Red Sands of the Arabian Desert, see J. A. Phillips, Q. J. Geol. Soc. xxxviii. (1882), p. 110, also op. cit. xxxvii. (1881), p. 12.

cerned with a microscope. The smaller forms are generally less well rounded than those of greater dimensions, no doubt because their diminutive size allows them to remain suspended in agitated water, and thus to escape the mutual attrition to which the larger and heavier grains are exposed upon the bottom. (Book III. Part II. Section ii.) So far as experience has yet gone, there is no method by which inorganic sea-sand can be distinguished from that of rivers or lakes. As a rule, sand consists largely (often wholly) of quartz-grains. The presence of fragments of marine shells will of course betray its salt-water origin; but in the trituration to which sand is exposed on a coast-line, the shell-fragments are in great measure ground into calcareous mud and removed.

Mr. Sorby has shown that, by microscopic investigation, much information may be obtained regarding the history and source of sedimentary materials. He has studied the minute structure of modern sand, and finds that sand-grains present the following five distinct types, which, however, graduate into each other.

1. Normal, angular, fresh-formed sand, such as has been derived almost directly from the breaking up of granitic or schistose rocks.

2. Well-worn sand in rounded grains, the original angles being completely lost, and the surfaces looking like fine ground glass.

3. Sand mechanically broken into sharp angular chips, showing a glassy fracture.

4. Sand having the grains chemically corroded, so as to produce a peculiar texture of the surface, differing from that of worn grains or crystals.

5. Sand in which the grains have a perfectly crystalline outline, in some cases undoubtedly due to the deposition of quartz upon rounded or angular nuclei of ordinary non-crystalline sand.[112]

The same acute observer points out that, as in the familiar case of conglomerate pebbles, which have sometimes been used over again in conglomerates of very different ages, so with the much more minute grains of sand, we must distinguish between the age of the grains and the age of the deposit formed of them. An ancient sandstone may consist of grains that had hardly been worn before they were

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[112] Address, Q. J. Geol. Soc. xxxvi. (1880), p. 58, and Monthly Microscop. Journ. Anniv. Address, 1877.

finally brought to rest, while the sand of a modern beach may have been ground down by the waves of many successive geological periods.

Sand taken by Mr. Sorby from the old gravel terraces of the River Tay was found to be almost wholly angular, indicating how little wear and tear there may be among particles of quartz $\frac{1}{100}$ of an inch in diameter, even though exposed to the drifting action of a rapid river.[113] Sand from the bowlder clay at Scarborough was likewise ascertained to be almost entirely fresh and angular. On the other hand, in geological formations which can be traced in a given direction for several hundred miles, a progressively large proportion of rounded particles may be detected in the sandy beds, as Mr. Sorby has found in following the Greensand from Devonshire to Kent. In wind-blown sand exposed for a long period to drift to and fro along the surface the larger particles and pebbles acquire a remarkably smoothed and polished surface.

The occurrence of various other minerals besides quartz in ordinary sand has long been recognized, but we owe to the recent observations of Mr. A. B. Dick the discovery that among these minerals some of the most plentiful and most perfectly preserved belong to species that were not supposed to be so widely diffused, such as zircon, rutile, and tourmaline. He has found that these heavy minerals constitute sometimes as much as 4 per cent of the Bagshot sand of the older Tertiary series of the London basin.[114] Felspars, micas, hornblendes, pyroxenes, magnetite, glauconite and other minerals may likewise be recognized. The remarkable perfection of some of the crystallographic forms of the minuter mineral constituents of certain sands has been well shown by Mr. Dick.

Varieties of river- or sea-sand may be distinguished by names referring to some remarkable constituent, *e.g.* magnetic sand, iron-sand, gold-sand, auriferous sand, etc.

Gravel, Shingle—names applied to the coarser kinds of rounded water-worn detritus. In Gravel, the average size of the component pebbles ranges from that of a small pea up to about that of a walnut, though of course many included fragments will be observed which exceed these limits. In Shingle, the stones are coarser, ranging up to blocks as big

113 See Book III. Part II. Section ii. § 3.

114 Nature, xxxvi. (1887), p. 91, Mem. Geol. Surv. "Geology of London," vol. i. (1889), p. 523. Teall, "Microscopic Petrography," Plate xliv.

as a man's head or larger. German geologists distinguish as "schotter," a shingle containing dispersed bowlders, and "schotter-conglomerate," a rock wherein these materials have become consolidated.[115] All these names are applied quite irrespective of the composition of the fragments, which varies greatly from point to point. As a rule, the stones consist of hard rocks, since these are best fitted to withstand the powerful grinding action to which they are exposed.

Conglomerate (Puddingstone)—a rock formed of consolidated gravel or shingle. The component pebbles are rounded and water-worn. They may consist of any kind of rock, though usually of some hard and durable sort, such as quartz or quartzite. A special name may be given according to the nature of the pebbles, as quartz-conglomerate, limestone-conglomerate, granite-conglomerate, etc., or according to that of the paste or cementing matrix, which may consist of a hardened sand or clay, and may be siliceous, calcareous, argillaceous, or ferruginous. In the coarser conglomerates, where the blocks may exceed six feet in length, there is often very little indication of stratification. Except where the flatter stones show by their general parallelism the rude lines of deposit, it may be only when the mass of conglomerate is taken as a whole, in its relation to the rocks below and above it, that its claim to be considered a bedded rock will be conceded. The occurrence of occasional bands of conglomerate in a series of arenaceous strata is analogous probably to that of a shingle-bank or gravel-beach on a modern coast-line. But it is not easy to understand the circumstances under which some ancient conglomerates accumulated, such as that of the Old Red Sandstone of Central Scotland, which attains a thickness of many thousand feet, and consists of well-rounded and smoothed blocks often several feet in diameter.

In many old conglomerates (and even in those of Miocene age in Switzerland) the component pebbles may be observed to have indented each other. In such cases also they may be found elongated, distorted or split and recemented; sometimes the same pebble has been crushed into a number of pieces, which are held together by a retaining cement. These phenomena point to great pressure, and some internal

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[115] See, for example, an account of the schotter-conglomerates of Northern Persia by E. Tietze, Jahrb. Geol. Reichsanst. Vienna, 1881, p. 68.

relative movement in the rocks. (Book III. Part I. Section iv. § 3.)

Breccia—a rock composed of angular, instead of rounded, fragments. It commonly presents less trace of stratification than conglomerate. Intermediate stages between these two rocks, where the stones are partly angular and partly subangular and rounded, are known as *brecciated conglomerate.* Considered as a detrital deposit formed by superficial waste, breccia points to the disintegration of rocks by the atmosphere, and the accumulation of their fragments with little or no intervention of running water. Thus it may be formed at the base of a cliff, either subaerially, or where the débris of the cliff falls at once into a lake or into deep sea-water.

The term Breccia has, however, been applied to rocks formed in a totally different manner. Angular blocks of all sizes and shapes have been discharged from volcanic orifices, and, falling back, have consolidated there into masses of brecciated material (volcanic breccia). Intrusive igneous eruptions have sometimes torn off fragments of the rocks through which they have ascended, and these angular fragments have been inclosed in the liquid or pasty mass. Or the intrusive rock has cooled and solidified externally while still mobile within, and in its ascent has caught up and involved some of these consolidated parts of its own substance. Again, where solid masses of rock within the crust of the earth have ground against each other, as in dislocations, angular fragmentary rubbish has been produced, which has subsequently been consolidated by some infiltrating cement (Fault-rock). It is evident, however, that breccia formed in one or other of these hypogene ways will not, as a rule, be apt to be mistaken for the true breccias, arising from superficial disintegration.

Sandstone (Grès)[116]—a rock composed of consolidated sand. As in ordinary modern sand, the integral grains of sandstone are chiefly quartz, which must here be regarded as the residue left after all the less durable minerals of the original rocks have been carried away in solution or in suspension as fine mud. The colors of sandstones arise, not so much from that of the quartz, which is commonly white or gray, as from the film or crust which often coats the grains and holds

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[116] See J. A. Phillips on the constitution and history of grits and sandstones. Quart. Journ. Geol. Soc. xxxvii. (1881), p. 6. For analyses of some British sandstones used as building stones, see Wallace, Proc. Phil. Soc. Glasgow, xiv. (1883), p. 22.

them together as a cement. Iron, the great coloring ingredient of rocks, gives rise to red, brown, yellow, and green hues, according to its degree of oxidation and hydration.

Like conglomerates, sandstones differ in the nature of their component grains, and in that of the cementing matrix. Though consisting for the most part of siliceous grains, they include others of clay, felspar, mica, zircon, rutile, tourmaline, or other minerals such as occur in sand (p. 227), and these may increase in number so as to give a special character to the rock. Thus, sandstones may be argillaceous, felspathic, micaceous, calcareous, etc. By an increase in the argillaceous constituents, a sandstone may pass into one of the clay-rocks, just as modern sand on the sea-floor shades imperceptibly into mud. On the other hand, by an augmentation in the size and sharpness of the grains, a sandstone may become a grit, and by an increase in the size and number of pebbles may pass into a pebbly or conglomeratic sandstone, and thence into a fine conglomerate. A piece of fine-grained sandstone, seen under the microscope, looks like a coarse conglomerate, so that the difference between the two rocks is little more than one of relative size of particles.

The cementing material of sandstones may be *ferruginous*, as in most ordinary red and yellow sandstones, where the anhydrous or hydrous iron-oxide is mixed with clay or other impurity—in red sandstones the grains are held together by a hæmatitic, in yellow sandstones by a limonitic cement; *argillaceous*, where the grains are united by a base of clay, recognizable by the earthy smell when breathed upon; *calcareous*, where carbonate of lime occurs either as an amorphous paste or as a crystalline cement between the grains; *siliceous*, where the component particles are bound together by silica, as in the exposed blocks of Eocene sandstone known as "grayweathers" in Wiltshire, and which occur also over the north of France toward the Ardennes.

Among the varieties of sandstone the following may here be mentioned. Flagstone—a thin-bedded sandstone, capable of being split along the lines of stratification into thin beds or flags; Micaceous sandstone (*mica-psammite*)—a rock so full of mica-flakes that it splits readily into thin laminæ, each of which has a lustrous surface from the quantity of silvery mica. This rock is called "fakes" in Scotland. Freestone—a sandstone (the term being applied sometimes also to limestone) which can be cut into blocks in any direction, without a marked tendency to split in any one plane more than in another. Though this rock occurs in beds, each bed is not divided into laminæ, and it is the absence of this minor stratification which makes the stone so useful for architectural purposes (Craigleith and other sandstones at Edinburgh, some of which contain 98 per cent of silica). Glauconitic sandstone (green-sand)—a sandstone containing kernels and dusty grains of glauconite, which imparts a general greenish hue to the rock. The glauconite has probably been deposited in association with decaying organic matter, as where it fills echinus-spines, foraminifera, shells and corals on the floor of the present ocean.[117] Buhrstone—a highly siliceous, exceedingly compact, though cellular rock (with *Chara* seeds, etc.), found alternating with unaltered Tertiary strata in the Paris basin, and forming from its hardness and roughness an excellent material for the grindstones of flour-mills, may be mentioned here, though it probably has been formed by the precipitation of silica through the action of organisms. Arkose (*granitic sandstone*)—a rock composed of disintegrated granite, and found in geological formations of different ages, which have been derived from granitic rocks. Crystallized sandstone—an arenaceous rock in which a deposit of crystalline quartz has taken place upon the individual grains, each of which becomes the nucleus of a more or less perfect quartz crystal. Mr. Sorby has observed such crystallized sand in deposits of various ages from the Oolites down to the Old Red Sandstone.[118]

Graywacke—a compact aggregate of rounded or subangular grains of quartz, felspar, slate, or other minerals or rocks, cemented by a paste which is usually siliceous, but may be argillaceous, felspathic, calcareous, or anthracitic (Fig. 21). Gray, as its name denotes, is the prevailing color: but it passes into brown, brownish-purple, and sometimes, where anthracite predominates, into black. The rock is distinguished from ordinary sandstone by its darker hue, its hardness, the variety of its component grains, and, above all, by the compact cement in which the grains are imbedded. In many varieties, so pervaded is the rock by the siliceous paste, that it possesses great toughness, and its grains seem to graduate into each other as well as into the surrounding

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117 Ante, p. 141; Sollas, Geol. Mag. iii. 2d ser. p. 539.

118 Q. J. Geol. Soc. xxxvi. p. 63. See Daubrée, Ann. des Mines, 2d ser. i. p. 206. A. A. Young, Amer. Journ. Sci. 3d ser. xxiii. 257; xxiv. 47, and especially the work of Irving and Van Hise (quoted on p. 196), which gives some excellent figures of enlarged quartz-grains.

matrix. Such rocks, when fine-grained, can hardly, at first sight or with the unaided eye, be distinguished from some compact igneous rocks, though a microscopic examination at once reveals their fragmental character. In other cases, where the graywacke has been formed mainly out of the débris of granite, quartz-porphyry, or other felspathic masses, the grains consist so largely of felspar, and the paste also is so felspathic, that the rock might be mistaken for some close-grained granular porphyry. Graywacke occurs extensively among the Palæozoic formations, in beds alternating with shales and conglomerates. It represents the muddy sand of some of the Palæozoic sea-floors, retaining often its ripple-marks and sun-cracks. The metamorphism it has undergone has generally not been great, and for the most part is limited to induration, partly by pressure and partly by permeation of a siliceous cement. But where felspathic ingredients prevail, the rock has offered facilities for alteration, and has been here and there changed into highly crystalline mica-schists full of garnets and other secondary minerals (contact-metamorphism at the granite of New Galloway, Scotland, postea, Book IV. Part VIII.).

The more fissile fine-grained varieties of this rock have been termed graywacke-slate (p. 238). In these, as well as in graywacke, organic remains occur among the Silurian and Devonian formations. Sometimes in the Lower Silurian rocks of Scotland, these strata become black with carbonaceous matter, among which vast numbers of graptolites may be observed. Gradations into sandstone are termed Graywacke-sandstone. In Norway the reddish felspathic graywacke or sandstone of the Primordial rocks is called Sparagmite; similar material forms much of the Torridon sandstone of Scotland.

Quartzite.—An altered siliceous sandstone (see p. 311).

2. **Clay Rocks** (Pelites)

These are composed of fine argillaceous sediment or mud, derived from the waste of rocks. Perfectly pure clay or kaolin, hydrated silicate of alumina, may be obtained where granites and other felspar-bearing rocks decompose. But, as a rule, the argillaceous materials are mixed with various impurities.

Clay, Mud.—The decomposition of felspars and allied minerals gives rise to the formation of hydrous aluminous silicates, which, occurring usually in a state of fine subdivision, are capable of being held in suspension in water, and of being transported to great distances. These substances, differing much in composition, are embraced under the general term Clay, which may be defined as a white, gray, brown, red, or bluish substance, which when dry is soft and friable, adheres to the tongue, and shaken in water makes it mechanically turbid; when moist is plastic, when mixed with much water becomes mud. It is evident that a wide range is possible for varieties of this substance. The following are the more important.

Kaolin (Porcelain-clay, China-clay) has been already noticed (p. 140).

Pipe-clay—white, nearly pure, and free from iron.

Fire-clay—largely found in connection with coal-seams, contains little iron, and is nearly free from lime and alkalies. Some of the most typical fire-clays are those long used as Stourbridge, Worcestershire, for the manufacture of pottery. The best glass-house pot-clay, that is, the most refractory, and therefore used for the construction of pots which have to stand the intense heat of a glass-house, has the following composition: silica, 73·82; alumina, 15·88; protoxide of iron, 2·95; lime, trace; magnesia, trace; alkalies, ·90; sulphuric acid, trace; chlorine, trace; water, 6·45; specific gravity, 2·51.

Cannister—a very siliceous close-grained variety, found in the Lower Coal measures of the North of England, and now largely ground down as a material for the hearths of iron furnaces.

Brick-clay—properly rather an industrial than a geological term, since it is applied to any clay, loam, or earth, from which bricks or coarse pottery are made. It is an impure clay, containing a good deal of iron, with other ingredients. An analysis gave the following composition of a brick-clay: silica, 49·44; alumina, 34·26; sesquioxide of iron, 7·74; lime, 1·48; magnesia, 5·14; water, 1·94.

Fuller's Earth (Terre à foulon, Walkerde)—a greenish or brownish, earthy, soft, somewhat unctuous substance, with a shining streak, which does not become plastic with water, but crumbles down into mud. It is a hydrous aluminous silicate with some magnesia, iron-oxide and soda. The yellow fuller's earth of Reigate contains silica 44, alumina 11, oxide of iron 10, magnesia 2, lime 5, soda 5.[119] In England

[119] Ure's Dict. Arts, etc. ii. p. 142.

fuller's earth occurs in beds among the Jurassic and Cretaceous formations. In Saxony it is found as a result of the decomposition of diabase and gabbro.

Wacke—a dirty-green to brownish-black, earthy or compact, but tender and apparently homogeneous clay, which arises as the ultimate stage of the decomposition of basalt-rocks *in situ*.

Loam—an earthy mixture of clay and sand with more or less organic matter. The black soils of Russia, India, etc. (Tchernosem, Regur), are dark deposits of loam rich in organic matter, and sometimes upward of twenty feet deep.

Loess—a pale, somewhat calcareous clay, probably of wind-drift origin, found in some river-valleys (Rhine, Danube, Mississippi, etc.), and over wide regions in China and elsewhere. It is described in Book III. Part. II. Sect. i. § 1.

Laterite—a cellular, reddish, ferruginous clay, found in some tropical countries as the result of the subaerial decomposition of rocks; it acquires great hardness after being quarried out and dried.

Till, Bowlder-clay—a stiff sandy and stony clay, varying in color and composition, according to the character of the rocks of the district in which it lies. It is full of worn stones of all sizes, up to blocks weighing several tons, and often well-smoothed and striated. It is a glacial deposit, and will be described among the formations of the Glacial Period.

Mudstone—a fine, usually more or less sandy, argillaceous rock, having no fissile character, and of somewhat greater hardness than any form of clay. The term C l a y-r o c k has been applied by some writers to an indurated clay requiring to be ground and mixed with water before it acquires plasticity.

Shale (Schiste, Schieferthon)—a general term to describe clay that has assumed a thinly stratified or fissile structure. Under this term are included laminated and somewhat hardened argillaceous rocks, which are capable of being split along the lines of deposit into thin leaves. They present almost endless varieties of texture and composition, passing, on the one hand, into clays, or, where much indurated, into slates and argillaceous schists, on the other, into flagstones and sandstones, or again, through calcareous gradations into limestone, or through ferruginous varieties into clay-ironstone, and through bituminous kinds into coal.

Clay-slate (Schiste ardoise, Thonschiefer).—Under this name are included certain hard fissile argillaceous masses, composed primarily of compact clay, sometimes with megascopic and microscopic scales of one or more micaceous minerals, granules of quartz and cubes or concretions of pyrites, as well as veins of quartz and calcite. The fissile structure is specially characteristic. In some cases this structure coincides with that of original deposit, as is proved by the alteration of fissile beds with bands of hardened sandstone, conglomerate or fossiliferous limestone. But for the most part as the rocks have been much compressed, the fissile structure of the argillaceous bands is independent of stratification, and can be seen traversing it. Sorby has shown that this superinduced fissility or "cleavage" has resulted from an internal rearrangement of the particles in planes perpendicular to the direction in which the rocks have been compressed (see Book III. Part I. Section iv. § 3). In England the term "slate" or "clay-slate" is given to argillaceous, not obviously crystalline rocks possessing this cleavage-structure. Where the micaceous lustre of the finely disseminated superinduced mica is prominent, the rocks are phyllites.

Microscopic examination shows that while some argillaceous rocks consist mainly of granular débris, many cleaved clay-slates contain a large proportion of a micaceous mineral in extremely minute flakes, which in the best Welsh slates have an average size of $\frac{1}{2000}$ of an inch in breadth, and $\frac{1}{6000}$ of an inch in thickness, together with very fine black hairs which may be magnetite.[120] Moreover, many clay-slates, though to outward appearance thoroughly noncrystalline, and evidently of fragmental composition and sedimentary origin, yet contain, sometimes in remarkable abundance, microscopic microlites and crystals of different minerals placed with their long axes parallel with the planes of fissility. These minute bodies include yellowish-brown needles of rutile, greenish or yellowish flakes of mica, scales of calcite, and probably other minerals.[121] Small granules of quartz containing fluid-cavities, show on their surfaces a distinct blending with the substance of the surrounding

[120] Sorby, Q. J. Geol. Soc. xxvi. p. 68.

[121] These "clay-slate needles" were probably not crystallized contemporaneously with the deposit of the original rock. In some cases they may have been deposited with the rest of the sediment as part of the débris of pre-existing crystalline rocks (see p. 228); but in general they appear to have been developed where they now occur by subsequent actions (see postea, pp. 531, 532). For their character see Zirkel, "Mik. Beschaff." p. 490. Kalkowsky, N. Jahrb. 1879, p. 382; A. Cathrein, op. cit. 1882 (i.) p. 169. F. Penck, Sitzb. Bayer. Akad. Math. Phys. 1880, p. 461. A. Wichmann, Q. J. Geol. Soc. xxxv. p. 156.

rock. M. Renard has found that the Belgian whet-slate is full of minute crystals of garnet.[122] Some of the more crystalline varieties (phyllite) are almost wholly composed of minute crystalline particles of mica, quartz, felspar, chlorite, and rutile, and form an intermediate stage between ordinary clay-slate and mica-schist.

A distinction has been drawn by some petrographers between certain rocks (phyllite, Urthonschiefer) which occur in Archæan regions or in groups probably of high antiquity, and others (ardoise, Thonschiefer) which are found in Palæozoic and later formations. But there does not appear to be adequate justification for this grouping, which has probably been suggested rather by theoretical exigencies than by any essential differences between the rocks themselves. That the whole of the series of argillaceous rocks, beginning with clay and passing through shale into slate and phyllite, is of sedimentary origin is indicated by the organic remains, false bedding, ripple-mark, etc., found in those at one end of the series, and by the insensible gradation of the mineralogical characters through increasing stages of metamorphism to the other end. Some microscopic crystals may possibly have been originally formed among the muddy sediment on the sea-floor (see p. 770). Others may have formed part of the original mechanical detritus that went to make the slate. But, for the most part, they have been subsequently developed within the rock, and represent early stages of the process which has culminated in the production of crystalline schists. The development of crystals of chiastolite and other minerals in clay-slate is frequently to be observed round bosses of granite, as one of the phases of contact-metamorphism.

A number of varieties of Clay-slate are recognized. Roofing slate (Dachschiefer) includes the finest, most compact, homogeneous and durable kinds, suitable for roofing houses or the manufacture of tables, chimney-pieces, writing-slates, etc.; it occurs in the Silurian and Devonian formations of Central and Western Europe. Anthracitic-slate (anthracite-phyllite, alum-slate), dark carbonaceous slate with much iron-disulphide. Bands of this nature sometimes run through a clay-slate region. The

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122 Acad. Roy. Belgique, xli. (1877). See also his paper on the composition and structure of the phyllades of the Ardennes, Bull. Mus. Roy. Belg. iii. (1884), p. 231.

carbonaceous material arises from the alteration of the remains of plants (fucoids) or animals (frequently graptolites). The marcasite so abundantly associated with these organisms decomposes on exposure, and the sulphuric acid produced, uniting with the alumina, potash, and other bases of the surrounding rocks, gives rise to an efflorescence of alum, or the decomposition produces sulphurous springs like those of Moffat. The name Graywacke-slate has been applied to extremely fine-grained, hard, shaly, more or less micaceous and sandy bands, associated with graywacke among the older Palæozoic rocks. Whet-slate, Novaculite, Hone-stone, is an exceedingly hard fine-grained siliceous rock, some varieties of which derive their economic value from the presence of microscopic crystals of garnet. The various forms of altered clay-slate are described at p. 309 among the metamorphic rocks.

Porcellanite (Argillite) or baked shale—a name applied to the exceedingly indurated sometimes partially fused condition which shales are apt to assume in contact with dikes and intrusive sheets or bosses. For an account of this form of contact-metamorphism see Book IV. Part VIII.

3. Volcanic Fragmental Rocks—Tuffs

This section comprises all deposits which have resulted from the comminution of volcanic rocks. They thus include (1) those which consist of the fragmentary materials ejected from volcanic foci, or the true ashes and tuffs; and (2) some rocks derived from the superficial disintegration of already erupted and consolidated volcanic masses. Obviously the second series ought properly to be classed with the sandy or clayey rocks above described, since they have been formed in the same way. In practice, however, these detrital reconstructed rocks cannot always be certainly distinguished from those which have been formed by the consolidation of true volcanic dust and sand. Their chemical and lithological characters, both megascopic and microscopic, are occasionally so similar, that their respective modes of origin have to be decided by other considerations, such as the occurrence of lapilli, bombs, or slags in the truly volcanic series, and of well water-worn pebbles of volcanic rocks in the other. Attention to these features, however, usually enables the geologist to make the distinction, and to perceive that the number of instances where he may be in doubt is less than might be supposed. Only a comparatively small number of the rocks classed here are not true volcanic ejections.[123]

Referring to the account of volcanic action in Book III. Part I. Sect. i., we may here merely define the use of the names by which the different kinds of ejected volcanic materials are known.

Volcanic Blocks—angular, sub-angular, round, or irregularly-shaped masses of lava, several feet in diameter, sometimes of uniform texture throughout, as if they were large fragments dislodged by explosion from a previously consolidated rock, sometimes compact in the interior and cellular or slaggy outside.

Bombs—round, elliptical, or discoidal pieces of lava from a few inches up to one or more feet in diameter. They are frequently cellular internally, while the outer parts are fine-grained. Occasionally they consist of a mere shell of lava with a hollow interior like a bombshell, or of a casing of lava inclosing a fragment of rock. Their mode of origin is explained in Book III. Part I. Sect. i. § 1.

Lapilli (rapilli)—ejected fragments of lava, round, angular, or indefinite in shape, varying in size from a pea to a walnut. Their mineralogical composition depends upon that of the lava from which they have been thrown up. Usually they are porous or finely vesicular in texture.

Volcanic Sand, Volcanic Ash—the finer detritus erupted from volcanic orifices, consisting partly of rounded and angular fragments up to about the size of a pea derived from the explosion of lava within eruptive vents, partly of vast quantities of microlites and crystals of some of the minerals of the lava. The finest dust is in a state of extremely minute subdivision. When examined under the microscope, it is sometimes found to consist not only of minute crystals and microlites, but of volcanic glass, which may be observed adhering to the microlites or crystals round which it flowed when still part of the fluid lava. The presence of minutely cellular fragments is characteristic of most volcanic fragmental rocks, and this structure may commonly be observed in the microscopic fragments and filaments of glass.

When these various materials are allowed to accumulate, they become consolidated and receive distinctive names. In cases where they fall into the sea or into lakes, they are liable at the outer margin of their area to be mingled with,

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[123] For a classification of tuffs and tuffaceous deposits see E. Reyer, Jahrb. K. K. Geol. Reichsanst. xxxi. (1881), p. 57.

and insensibly to pass into ordinary non-volcanic sediment. Hence we may expect to find transitional varieties between rocks formed directly from the results of volcanic explosion and ordinary sedimentary deposits.

Volcanic Conglomerate—a rock composed mainly or entirely of rounded or sub-angular fragments, chiefly or wholly of volcanic rocks, in a paste of the same materials, usually exhibiting a stratified arrangement, and often found intercalated between successive sheets of lava. Conglomerates of this kind may have been formed by the accumulation of rounded materials ejected from volcanic vents; or as the result of the aqueous erosion of previously solidified lavas, or by a combination of both these processes. Well-rounded and smoothed stones almost certainly indicate long-continued water-action, rather than trituration in a volcanic vent. In the Western Territories of the United States vast tracts of country are covered with masses of such conglomerate, sometimes 2000 feet thick. Captain Dutton has shown that similar deposits are in course of formation there now, merely by the influence of disintegration upon exposed lavas.[124]

Volcanic conglomerates receive different names according to the nature of the component fragments; thus we have *basalt-conglomerates*, where these fragments are wholly or mainly of basalt, *trachyte-conglomerates*, *porphyrite-conglomerates*, *phonolite-conglomerates*, etc.

Volcanic Breccia resembles Volcanic Conglomerate, except that the stones are angular. This angularity indicates an absence of aqueous erosion, and, under the circumstances in which it is found, usually points to immediately adjacent volcanic explosions. There is a great variety of breccias, as *basalt-breccia*, *diabase-breccia*, etc.

Volcanic Agglomerate—a tumultuous assemblage of blocks of all sizes up to masses several yards in diameter, met with in the "necks" or pipes of old volcanic orifices. The stones and paste are commonly of one or more volcanic rocks, such as felsite, porphyrite or basalt, but they include also fragments of the surrounding rocks, whatever these may be, through which the volcanic orifice has been drilled. As a rule, agglomerate is devoid of stratification; but sometimes it includes portions which have a more or less distinct arrangement into beds of coarser and finer detritus, often placed on end, or inclined in different directions at high angles, as described in Book IV. Part VII. Sect. i. § 4.

124 "High Plateaus of Utah," p. 77.

Volcanic Tuff.—This general term may be made to include all the finer kinds of volcanic detritus, ranging, on the one hand, through coarse gravelly deposits into conglomerates, and on the other, into exceedingly compact fine-grained rocks, formed of the finest and most impalpable kind of volcanic dust. Some modern tuffs are full of microlites, derived from the lava which was blown into dust. Others are formed of small rounded or angular grains of different lavas, with fragments of various rocks through which the volcanic funnels have been drilled. The tuffs of earlier geological periods have often been so much altered, that it is difficult to state what may have been their original condition. The absence of microlites and glass in them is no proof that they are not true tuffs; for the presence of these bodies depends upon the nature of the lavas. If the latter were not vitreous and microlitic, neither would be the tuffs derived from them. In the Carboniferous volcanic area of Central Scotland, the tuffs are made up of débris and blocks of the basaltic lavas, and, like these, are not microlitic, though in some places they abound in fragments of the basic glass called palagonite. (Fig. 23, and *infra*, p. 242.)

Fig. 23.—Microscopic Structure of Carboniferous Palagonite Tuff from Burntisland, Fife.

Tuffs have consolidated sometimes under water, sometimes on dry land. As a rule, they are distinctly stratified. Near the original vents of eruption they commonly present rapid alternations of finer and coarser detritus, indicative of successive phases of volcanic activity. They necessarily shade off into the sedimentary formations with which they were contemporaneous. Thus, we have tuffs passing gradually into shale, limestone, sandstone, etc. The intermediate varieties have been called *ashy shale*, *tuffaceous shale*, or *shaly tuff*, etc. From the circumstances of their formation, tuffs frequently preserve the remains of plants and animals, both terrestrial and aquatic. Those of Monte Somma contain fragments of land-plants and shells. Some of those of Carboniferous age in Central Scotland have yielded crinoids, brachiopods, and other marine organisms. Like the other fragmentary volcanic rocks, the tuffs may be subdivided according to the nature of the lava from the disintegration of which they have been formed. Thus we have *felsite-tuffs*, *trachyte-tuffs*, *basalt-tuffs*, *pumice-tuffs*, *porphyrite-tuffs*, etc. A few varieties with special characteristics may be mentioned here.[125]

Trass—a pale yellow or gray rock, rough to the feel, composed of an earthy or compact pumiceous dust, in which fragments of pumice, trachyte, graywacke, basalt, carbonized wood, etc., are imbedded. It has filled up some of the valleys of the Eifel, where it is largely quarried as a hydraulic mortar.

Peperino—a dark-brown, earthy or granular tuff, found in considerable quantity among the Alban Hills near Rome, and containing abundant crystals of augite, mica, leucite, magnetite, and fragments of crystalline limestone, basalt, and leucite-lava.

Palagonite-Tuff—a bedded aggregate of dust and fragments of basaltic lava, among which are conspicuous angular pieces and minute granules of the pale yellow, green, red, or brown basic glass called palagonite. This vitreous substance is intimately related to the basalts (p. 298). It appears to have gathered within volcanic vents and to have been emptied thence, not in streams, but by successive aeriform explosions, and to have been subsequently more or less altered. The percentage composition of a specimen from the typical locality, Palagonia, in the Val di Noto, Sicily, was estimated by Sartorius von Waltershausen to be: silica, 41·26; alumina, 8·60; ferric oxide, 25·32; lime, 5·59; magnesia, 4·84; potash, 0·54; soda, 1·06; water, 12·79. This rock is largely developed among the products of the Icelandic and Sicilian volcanoes; it occurs also in the Eifel and in Nassau. It has been found to be one of the characteristic features of tuffs of Carboniferous age in Central Scotland[126] (Fig. 23).

Schalstein.—Under this name, German petrographers have placed a variety of green, gray, red, or mottled fissile rocks, impregnated with carbonate of lime. They are inter-stratified with the Devonian formations of Nassau, the Harz and

[125] On the occurrence and structure of tuffs, see J. C. Ward, Q. J. Geol. Soc. xxxi. p. 388; Reyer, Jahrb. Geol. Reichsanst. 1881, p. 57; Geikie, Trans. Roy. Soc. Edin. xxix.; Vogelsang, Z. Deutsch. Geol. Ges. xxiv. p. 543; Penck, op. cit. xxxi. p. 504. On the basalt-tuffs of Scania, F. Eichstadt, Sveriges Geol. Undersökn, ser. c. No. 58 (1883). On the metamorphism of tuffs into lava-like rocks, see Dutton's "High Plateaux of Utah" (U. S. Geograph. and Geol. Survey of Rocky Mounts.), 1880, p. 79.

[126] Trans. Roy. Soc. Edin. xxix. p. 514.

Devonshire, and with the Silurian rocks of Bohemia. They sometimes contain fragments of clay-slate, and are occasionally fossiliferous. They present amygdaloidal and porphyritic, as well as perfectly laminated structures. Probably they are in most cases true diabase-tuffs, but sometimes they may be forms of diabase-lavas, which, like the stratified formations in which they lie, have undergone alteration, and in particular have acquired a more or less distinctly fissile structure, as the result of lateral pressure and internal crushing.[127]

4. Fragmental Rocks of Organic Origin

This series includes deposits formed either by the growth and decay of organisms *in situ*, or by the transport and subsequent accumulation of their remains. These may be conveniently grouped, according to their predominant chemical ingredient, into Calcareous, Siliceous, Phosphatic, Carbonaceous, and Ferruginous.

1. CALCAREOUS.—Besides the calcareous formations which occur among the stratified crystalline rocks as results of the deposition of chemical precipitates (p. 260), a more important series is derived from the remains of living organisms, either by growth on the spot or by transport and accumulation as mechanical sediment. To by far the larger part of the limestones intercalated in the rocky framework of our continents, an organic origin may with probability be assigned. It is true, as has been above mentioned (p. 216), that limestone, formed of the remains of animals or plants, is liable to an internal crystalline rearrangement, the effect of which is to obliterate the organic structure. Hence in many of the older limestones no trace of any fossils can be detected, and yet these rocks were almost certainly formed of organic remains. An attentive microscopic study of organic calcareous structures, and of the mode of their replacement by crystalline calcite, sometimes detects indications of former organisms, even in the midst of thoroughly crystalline materials.[128]

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[127] C. Koch, Jahrb. Ver. Nat. Nassau, xiii. (1858), 216, 238. J. A. Phillips, Q. J. Geol. Soc. xxxii. p. 155, xxxiv. p. 471.

[128] Sorby, Address to Geol. Society, February, 1879, and the paper of Messrs. Cornish and Kendall, cited *ante*, p. 216. Gümbel has suggested that the different durability of the calcite and aragonite organic forms may be due rather to structure than mineral composition.

Limestone, composed of the remains of calcareous organisms, is found in layers which range from mere thin laminæ up to massive beds several feet or even yards in thickness. In some instances, such as that of the Carboniferous or Mountain limestone of Britain and Belgium, and that of the Coal-measures in Wyoming and Utah, it occurs in continuous superposed beds to a united thickness of several thousand feet, and extends for hundreds of square miles, forming a rock out of which picturesque gorges, hills, and table-lands have been excavated.

Limestones of organic origin present every gradation of texture and structure, from mere soft calcareous mud or earth, evidently composed of entire or crumbled organisms, up to solid compact crystalline rock, in which indications of an organic source can hardly be perceived. Mr. Sorby, in the address already cited, called renewed attention to the importance of the form in which carbonate of lime is built up into animal structures. Quoting the opinion of Rose expressed in 1858, that the diversity in the state of preservation of different shells might be due to the fact that some of them had their lime as calcite, others as aragonite, he showed that this opinion is amply supported by microscopic examination. Even in the shells of a recent raised beach, he observed that the inner aragonite layer of the common mussel had been completely removed, though the outer layer of calcite was well preserved. In some shelly limestones containing casts, the aragonite shells have alone disappeared, and where these still remain represented by a calcareous layer, this has no longer the original structure, but is more or less coarsely crystalline, being in fact a pseudomorph of calcite after aragonite, and quite unlike contiguous calcite shells, which retain their original microscopical and optical characters.[129]

The following list comprises some of the more distinctive and important forms of organically-derived limestones.

Shell-Marl—a soft, white, earthy, or crumbling deposit, formed in lakes and ponds by the accumulation of the remains of shells and *Entomostraca* on the bottom. When such calcareous deposits become solid compact stone they are known as *fresh-water* (*lacustrine*) *limestones*. These are generally of a smooth texture, and either dull white, pale

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[129] The student will find the address from which these citations are made full of suggestive matter in regard to the origin and subsequent history of limestones.

gray, or cream-colored, their fracture slightly conchoidal, rarely splintery.

Lumachelle—a compact, dark gray or brown limestone, charged with ammonites or other fossil shells, which are sometimes iridescent, giving bright green, blue, orange, and dark red tints (fire-marble).

Calcareous (Foraminiferal) Ooze—a white or gray calcareous mud, of organic origin, found covering vast areas of the floor of the Atlantic and other oceans, and formed mostly of the remains of *Foraminifera*, particularly

Fig. 24.—Foraminiferal (Globigerina) Ooze, dredged by the "Challenger" Expedition in Lat. 50° 1′ S., Long. 123° 4′ E., from a depth of 1800 fathoms (magnified 50 Diameters).

of forms of the genus *Globigerina* (Fig. 24). Further account of this and other organic deep-sea deposits is given in Book III. Part II. Section iii.

Shell-Sand—a deposit composed in great measure or wholly of comminuted shells, found commonly on a low shelving coast exposed to prevalent on-shore winds. When thrown above the reach of the waves and often wetted by rain, or by trickling runnels of water, it is apt to become consolidated into a mass, owing to the solution and redeposit of lime round the grains of shell (p. 216).

Coral-rock—a limestone formed by the continuous growth of coral-building polyps. This substance affords an excellent illustration of the way in which organic structure may be effaced from a limestone entirely formed of the remains of once living animals. Though the skeletons of the reef-building corals remain distinct on the upper surface, those of their predecessors beneath them are gradually obliterated by the passage through them of percolating water, dissolving and redepositing calcium carbonate. We can thus understand how a mass of crystalline limestone may have been produced from one formed out of organic remains, without the action of any subterranean heat, but merely by the permeation of water from the surface.[130]

Chalk—a white soft rock, meagre to the touch, soiling the fingers, formed of a fine calcareous flour derived from the remains of *Foraminifera*, echinoderms, mollusks, and other marine organisms. By making thin slices of the rock and examining them under the microscope, Sorby has found that Foraminifera, particularly *Globigerina*, and single detached cells of comparatively shallow-water forms, probably constitute less than half of the rock by bulk (Fig. 22), the remainder consisting of detached prisms of the outer calcareous layer of *Inoceramus*, fragments of *Ostrea*, *Pecten*, echinoderms, spicules of sponges, etc. It is not quite like any known modern deep-sea deposit. A microscopic investigation of chalk from the neighborhood of Lille showed that, besides the usual organic constituents, the rock contains minute grains and crystals of quartz, tourmaline, zircon, rutile, garnet and felspars,[131] these minerals being among the most widely diffused and persistent ingredients in the finer sediments that are derived from the denudation of crystalline rocks (see p. 228).

Crinoidal (Encrinite) Limestone—a rock composed in great part of crystalline joints of encrinites, with *Foraminifera*, corals, and mollusks. It varies in color from white or pale gray, through shades of bluish-gray (sometimes yellow or brown, less commonly red) to a dark gray or even black color. It is abundant among Palæozoic formations, being in Western Europe especially characteristic of the lower part of the Carboniferous system.

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[130] See Dana's "Coral and Coral Islands," p. 354; also the account of the Devonian and Carboniferous limestones in the present volume. Dupont has shown that many of the massive limestones of Belgium have been formed by reef-like masses of *Stromatopora* or allied organisms.

[131] L. Cayeux, Ann. Soc. Géol. Nord. xvii. (1890), p. 283.

2. SILICEOUS.—Silica is directly eliminated from both fresh and salt water by the vital growth of plants and animals. (Book III. Part II. Section iii.)

Diatom-earth, Tripolite (Infusorial earth, Kieselguhr)—a siliceous deposit formed chiefly of the frustules of diatoms, laid down both in salt and in fresh water. Wide areas of it are now being deposited on the bed of the South Pacific (*Diatom-ooze*, Fig. 181). In Virginia, United States, an extensive tract occurs covered with diatom-earth to a depth of 40 feet. It likewise underlies peat-mosses, probably as an original lake-deposit. It is used as *Tripoli powder* for polishing purposes (see p. 807).

Radiolarian ooze—a pale chalk-like abysmal marine deposit consisting mainly of the remains of siliceous radiolarians and diatoms. It is further referred to in Book III. Part II. Section iii.

Flint (Silex, Feuerstein)—a gray or black, excessively compact rock, with the hardness of quartz and a perfect conchoidal fracture, its splinters being translucent on the edges. Consists of an intimate mixture of crystalline insoluble silica and of amorphous silica soluble in caustic potass. Its dark color, which can be destroyed by heat, arises chiefly from the presence of carbonaceous matter. Flint occurs principally as nodules, dispersed in layers through the Upper Chalk of England and the northwest of Europe. It frequently incloses organisms such as sponges, echini and brachiopods. It has been deposited from sea-water, at first through organic agency, and subsequently by direct chemical precipitation round the already deposited silica. (Book III. Part II. Section iii.) Chert (phtanite) is a name applied to impure calcareous varieties of flint, in layers and nodules which are found among the Palæozoic and later formations, especially but not exclusively in limestones.[132] In some cases, as in the spicules of sponges, the silica has had a directly organic origin, having been secreted from sea-water by the living organisms; in other cases, where, for example, we find a calcareous shell, or echinus, or coral converted into silica, it would seem that the substitution of silica for calcium-carbonate has been effected by a

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[132] Consult Hull and Hardman, Trans. Roy. Dublin Soc. i. (1878), p. 71. Renard, Bull. Acad. Roy. Belgique, 2d ser. vol. xlvi. p. 471; Sollas, Ann. Mag. Nat. Hist. vii. (1881), p. 141; Scientific Proc. Roy. Dublin Soc. vi. (1887), part. i. G. J. Hinde, Geol. Mag. 1887, p. 435. Bands of radiolarian chert occupy persistent horizons among the Lower Silurian rocks of southern Scotland.

process of chemical pseudomorphism, either after or during the formation of the limestone. The vertical ramifying masses of flint in Chalk show that the calcareous ooze had to some extent accumulated before the segregation of these masses.[133]

3. Phosphatic.—A few invertebrata contain phosphate of lime. Among these may be mentioned the brachiopods *Lingula* and *Orbicula*,[134] also *Conularia*, *Serpulites*, and some recent and fossil crustacea. The shell of the recent *Lingula ovalis* was found by Hunt to contain, after calcination, 61 per cent of fixed residue, which consisted of 85·70 per cent of phosphate of lime; 11·75 carbonate of lime, and 2·80 magnesia. The bones of vertebrate animals likewise contain about 60 per cent of phosphate of lime, while their excrement sometimes abounds in the same substance. Hence deposits rich in phosphate of lime have resulted from the accumulation of animal remains from Silurian times up to the present day. Associated with the Bala limestone, in the Lower Silurian series of North Wales, is a band composed of concretions cemented in a black, graphitic, slightly phosphatic matrix, and containing usually 64 per cent of phosphate of lime (phosphorite).[135] The tests of the trilobites and other organisms among the Cambrian rocks of Wales also contain phosphate of lime, sometimes to the extent of 20 per cent.[136] Phosphatic, though certainly far inferior in extent and importance to calcareous, and even to siliceous, formations, are often of singular geological interest. The following examples may serve as illustrations.[137]

Guano—a deposit consisting mainly of the droppings of sea-fowl, formed on islands in rainless tracts off the western coasts of South America and of Africa. It is a brown, light, powdery substance with a peculiar ammoniacal odor, and occurs in deposits sometimes more than 100 feet thick. Analyses of American guano give—combustible organic matter and acids, 11·3; ammonia (carbonate, urate, etc.), 31·7; fixed alkaline salts, sulphates, phosphates, chlorides, etc., 8·1; phosphates of lime and magnesia, 22·5; oxalate of lime, 2·6; sand and earthy matter, 1·6; water, 22·2. This

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133 On formation of chalk-flints, see Book III. Part II. Section iii. § 3.

134 Sterry Hunt, Amer. Journ. Soc. xvii. (1854), p. 236. Logan's "Geology of Canada," 1863, p. 461.

135 D. C. Davies, Q. J. Geol. Soc. xxxi. p. 357. 136 Hicks, op. cit. p. 368.

137 For an exhaustive account of deposits of phosphate of lime, see R. A. F. Penrose, Jr.; Bull. U. S. Geol. Surv. No. 46, 1888, also postea, Book III. Part II. Sect. iii. § 3.

remarkable substance is highly valuable as a source of artificial manures. (Book III. Part II. Section iii.)

Bone-Breccia—a deposit consisting largely of fragmentary bones of living or extinct species of mammalia, found sometimes under stalagmite on the floors of limestone caverns, more or less mixed with earth, sand, or lime. In some older geological formations, bone-beds occur, formed largely of the remains of reptiles or fishes, as the "Lias bone-bed," and the "Ludlow bone-bed."

Coprolitic nodules and beds[138]—are formed of the accumulated excrement (coprolites) of vertebrated animals. Among the Carboniferous shales of the basin of the Firth of Forth, coprolitic nodules are abundant, together with the bones and scales of the larger ganoid fishes which voided them: abundance of broken scales and bones of the smaller ganoids can usually be observed in the coprolites. Among the Lower Silurian rocks of Canada, numerous phosphatic nodules, supposed to be of coprolitic origin, occur.[139] The phosphatic beds of the Cambridgeshire Cretaceous rocks are now largely worked as a source of artificial manure. In popular and especially commercial usage, the word "coprolitic" is applied to nodular deposits which can be worked for phosphate of lime, though they may contain few or no true coprolites.

Phosphatic Chalk.—In the Chalk of France and Belgium, more sparingly in that of England, certain layers occur where the original calcareous matter has been replaced to a considerable extent by phosphate of lime. Such bands have frequently a brownish tint, which on examination is found to result from the abundance of minute brown grains composed mainly of phosphate. The foraminifera and other minuter or fragmentary fossils have been changed into this brown substance. The proportion of phosphate of lime ranges up to 45 per cent or more.[140]

4. CARBONACEOUS.—The formations here included have almost always resulted from the decay and entombment of vegetation on the spot where it grew, sometimes by the drifting of the plants to a distance and their consolidation

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[138] On the origin of phosphatic nodules and beds, see Gruner. Bull. Soc. Géol. France, xxviii. (2d ser.), p. 62. Martin, op. cit. iii. (3d ser.), p. 273.

[139] Logan's "Geology of Canada," p. 461.

[140] See A. F. Renard and J. Cornet, Bull. Acad. Roy. Belgique, xxi. (1891), p. 126. A. Strahan, Quart. Journ. Geol. Soc. xlvii. (1891).

there. (See Book III. Part II. Section iii. § 3.) In the latter case, they may be mingled with inorganic sediment, so as to pass into carbonaceous shale.

Peat—vegetable matter, more or less decomposed and chemically altered, found throughout temperate climates in boggy places where marshy plants grow and decay. It varies from a pale yellow or brown fibrous substance, like turf or compressed hay, in which the plant-remains are abundant and conspicuous, to a compact dark brown or black material, resembling black clay when wet, and some varieties of lignite when dried. The nature and proportions of the constituent elements of peat, after being dried at 100° C., are illustrated by the analysis of an Irish example which gave—carbon, 60·48; hydrogen, 6·10; oxygen, 32·55; nitrogen, 0·88; while the ash was 3·30. There is always a large proportion of water which cannot be driven off even by drying the peat. In the manufacture of compressed peat for fuel this constituent, which of course lessens the value of the peat as compared with an equal weight of coal, is driven off to a great extent by chopping the peat into fine pieces, and thereby exposing a large surface to evaporation. The ash varies in amount from less than 1·00 to more than 65 per cent, and consists of sand, clay, ferric oxide, sulphuric acid, and minute proportions of lime, soda, potash and magnesia.[141] Under a pressure of 6000 atmospheres peat is converted into a hard, black, brilliant substance having the physical aspect of coal, and showing no trace of organic structure.[142]

Lignite (Brown Coal)—compact or earthy, compressed and chemically altered vegetable matter, often retaining a lamellar or ligneous texture, with stems showing woody fibre crossing each other in all directions. It varies from pale brown or yellow to deep brown or black. Some shade of brown is the usual color, whence the name *Brown Coal*, by which it is often known. It contains from 55 to 75 per cent of carbon, has a specific gravity of 0·5 to 1·5, burns easily to a light ash with a sooty flame and a strong burned smell. It occurs in beds chiefly among the Tertiary strata, under conditions similar to those in which coal is found in

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[141] See Senft's "Humus-, Marsch-, Torf- und Limonit-bildungen," Leipzig, 1862. J. J. Früh, "Ueber Torf und Dopplerit, Zürich," 1883, and the various memoirs quoted postea, p. 802.

[142] Spring, Bull. Acad. Roy. Bruxelles, xlix. (1880), p. 367.

older formations. It may be regarded as a stage in the alteration and mineralization of vegetable matter, intermediate between peat and true coal.

Coal—a compact, usually brittle, velvet-black to pitch-black, iron-black, or dull, sometimes brownish rock, with a grayish-black or brown streak, and in some varieties a distinctly cubical cleavage, in others a conchoidal fracture. It contains from 75 to 90 per cent of carbon, and a small percentage of sulphur, generally in the form of iron-disulphide. It has a specific gravity of 1·2–1·35, and burns with comparative readiness, giving a clear flame, a strong aromatic or bituminous smell, some varieties fusing and caking into cinder, others burning away to a mere white or red

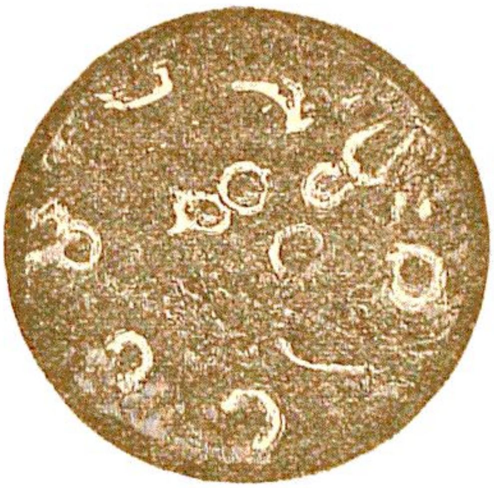

Fig. 25.—Microscopic Structure of Dalkeith **Coal**, showing Lycopodiaceous Sporangia (magnified 200 Diameters).

ash. Though it consists of compressed vegetation, no trace of organic structure is usually apparent.[143] An attentive examination, however, will often disclose portions of stems, leaves, etc., or at least of carbonized woody fibre. Some kinds are almost wholly made up of the spore-cases of lycopodiaceous plants (Fig. 25). There is reason to believe that different varieties of coal may have arisen from original diversities in the nature of the vegetation out of which they were formed. The accompanying table shows the chemical gradation between unaltered vegetation and the more highly mineralized forms of coal.

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[143] On the influence of pressure on the formation of coal, see Frémy, Compt. rend. 20th May 1879. Spring, Bull. Acad. Roy. Bruxelles, 1880, p. 367.

TABLE SHOWING THE GRADUAL CHANGE IN COMPOSITION FROM WOOD TO CHARCOAL[144]

Substance	Carbon.	Hydrogen.	Oxygen.	Disposable Hydrogen, *i.e.*, over and above what is required to form water.
1. Wood (mean of several analyses).......	100	12·18	83·07	1·80
2. Peat (" " ").......	100	9·85	55·67	2·89
3 Lignite (mean of 15 varieties)...........	100	8·37	42·42	3·07
4. Tan-yard coal of S. Staffordshire basin	100	6·12	21·23	3·47
5. Steam coal from the Tyne................	100	5·91	18·32	3·62
6. Pentrefelin coal of S. Wales.............	100	4·75	5·28	4·09
7. Anthracite from Pennsylvania, U. S...	100	2·84	1·74	2·63

Coal occurs in seams or beds intercalated between strata of sandstone, shale, fireclay, etc., in geological formations of Palæozoic, Secondary, and Tertiary age. It should be remembered that the word coal is rather a popular than a scientific term, being indiscriminately applied to any dense, black mineral substance capable of being used as fuel. Strictly employed, it ought only to be used with reference to beds of fossilized vegetation, the result either of the growth of plants on the spot or of the drifting of them thither.

The following analyses show the chemical composition of peat, lignite, and some of the principal varieties of coal:[145]

	Peat Devonshire	*Lignite* Bovey, Tracey, Devon	*Caking Coal* Northumberland	*Non-Caking Coal* S. Staffordshire	*Cannel Coal* Wigan	*Anthracite* S. Wales
Carbon	54·02	66·31	78·69	78·57	80·07	90·39
Hydrogen.................	5·21	5·63	6·00	5·29	5·53	3·28
Oxygen.....................	28·18	22·86	10·07	12·88	8·08	2·98
Nitrogen..................	2·30	0·57	2·37	1·84	2·12	0·83
Sulphur	0·56	2·36	1·51	0·39	1·50	0·91
Ash	9·73	2·27	1·36	1·03	2·70	1·61
Specific gravity......	0·850	1·129	1·259	1·278	1·276	1·392

144 Percy's "Metallurgy," vol. i. p. 268.
145 From Percy's "Metallurgy," vol. i.

These analyses are exclusive of water, which in the peat amounted to 25·56, and in the lignite to 34·66 per cent.

Anthracite—the most highly mineralized form of vegetation—is an iron-black to velvet-black substance, with a strong metalloidal to vitreous lustre, hard and brittle, containing over 90 per cent of carbon, with a specific gravity of 1·35–1·7. It kindles with difficulty, and in a strong draught burns without fusing, smoking, or smelling, but giving out a great heat. It is a coal from which the bituminous parts have been eliminated. It occurs in beds like ordinary coal, but in positions where probably it has been subjected to some change whereby its volatile constituents have been expelled. It is found largely in South Wales, and sparingly in the Scottish coal-fields where the ordinary coal-seams have been approached by intrusive masses of igneous rock. It is largely developed in the great coal-field of Pennsylvania. Some Lower Silurian shales are black from diffused anthracite, and have in consequence led to fruitless searches for coal.

Oil-shale (*Brandschiefer*)—shale containing such a proportion of hydrocarbons as to be capable of yielding mineral oil on slow distillation. This substance occurs as ordinary shales do, in layers or beds, interstratified with other aqueous deposits, as in the Scottish coal-fields. It is in a geological sense true shale, and owes its peculiarity to the quantity of vegetable (or animal) matter which has been preserved among its inorganic constituents. It consists of fissile argillaceous layers, highly impregnated with bituminous matter, passing on one side into common shale, on the other into cannel or parrot coal. The richer varieties yield from 30 to 40 gallons of crude oil to the ton of shale. They may be distinguished from non-bituminous or feebly bituminous shales (throughout the shale districts of Scotland), by the peculiarity that a thin paring curls up in front of the knife, and shows a brown lustrous streak. Some of the oil-shales in the Lothians are crowded with the valves of ostracod crustaceans, besides scales, coprolites, etc., of ganoid fishes. It is possible that the bituminous matter may in some cases have resulted from animal organisms, though the abundance of plant remains indicates that it is probably in most cases of vegetable origin. Under the name "pyroschists" Sterry Hunt classed the clays or shales (of all geological ages) which are hydrocarbonaceous, and yield by distillation volatile hydrocarbons, infammable gas, etc.

Petroleum—a general term, under which is included a series of natural mineral oils. These are fluid hydrocarbon compounds, varying from a thin, colorless, watery liquidity to a black, opaque, tar-like viscidity, and in specific gravity from 0·8 to 1·1. The paler, more limpid varieties are generally called naphtha, the darker, more viscid kinds mineral tar, while the name petroleum, or rock-oil, has been more generally applied to the intermediate kinds. Petroleum occurs sparingly in Europe. A few localities for it are known in Britain. It is found in large quantity along the country stretching from the Carpathians, through Gallicia and Moldavia, also at Baku on the Caspian.[146] The most remarkable and abundant display of the substance, however, is in the so-called oil-regions of North America, particularly in Western Canada and Northern Pennsylvania, where vast quantities of it have been obtained in recent years. In Pennsylvania it is found especially in certain porous beds of sandstone or "sand-rocks," which occur as low down as the Old Red Sandstone, or even as the top of the Silurian system. In Canada it is largely present in still lower strata. Its origin in these ancient formations, where it cannot be satisfactorily connected with any destructive distillation of coal, is still an unsolved problem.

Asphalt—a smooth, brittle, pitch-like, black or brownish-black mineral, having a resinous lustre and conchoidal fracture, streak paler than surface of fracture, and specific gravity of 1·0 to 1·68. It melts at about the temperature of boiling water, and can be easily kindled, burning with a bituminous odor and a bright but smoky flame. It is composed chiefly of hydrocarbons, with a variable admixture of oxygen and nitrogen. It occurs sometimes in association with petroleum, of which it may be considered a hardened oxidized form, sometimes as an impregnation filling the pores or chinks of rocks, sometimes in independent beds. In Britain it appears as a product of the destructive distillation of coals and carbonaceous shales by intrusive igneous rocks, as at Binny Quarry, Linlithgowshire, but also in a number of places where its origin is not evident, as in the Cornish and Derbyshire mining districts, and among the dark flagstones of Caithness and Orkney, which are laden with fossil fishes. At Seyssel (Département de l'Ain) it forms a deposit 2500 feet long and 800 feet broad, which yields 1500 tons annually. It exudes in a liquid form from the ground round the borders

[146] Abich, Jahrb. Geol. Reichsanst. xxix. (1879), p. 165. Trautschold, Zeitsch. Deutsch. Geol. Ges. xxvi. (1874), p. 257. See postea, Book III. Part I. Sect. i. § 2, where other authorities are cited.

of the Dead Sea. In Trinidad it forms a lake 1½ miles in circumference, which is cool and solid near the shore, but increases in temperature and softness toward the centre.

Graphite.—This mineral occurs in masses of sufficient size and importance to deserve a place in the enumeration of carbonaceous rocks. Its mineralogical characters have already (p. 124) been given. It occurs in distinct lenticular beds, and also diffused in minute scales, through slates, schists, and limestones of the older geological formations, as in Cumberland, Scotland, Canada, and Bohemia. It is likewise found occasionally as the result of the alteration of a coal seam by intrusive basalt, as at New Cumnock in Ayrshire.

5. Ferruginous.—The decomposition of vegetable matter in marshy places and shallow lakes gives rise to certain organic acids, which, together with the carbonic acid so generally also present, decompose the ferruginous minerals of rocks and carry away soluble salts of iron. Exposure to the air leads to the rapid decomposition and oxidation of those solutions, which consequently give rise to precipitates, consisting partly of insoluble basic salts and partly of the hydrated ferric oxide. These precipitates, mingled with clay, sand, or other mechanical impurity, and also with dead and decaying organisms, form deposits of iron-ore. Operations of this kind appear to have been in progress from a remote geological antiquity. Hence ironstones with traces of associated organic remains belong to many different geological formations, and are being formed still.[147]

Bog Iron-Ore (Lake-ore, minerai des marais, Sumpferz)—a dark-brown to black, earthy, but sometimes compact mixture of hydrated peroxide of iron, phosphate of iron, and hydrated oxide of manganese, frequently with clay, sand, and organic matter. An ordinary specimen yielded, peroxide of iron, 62·59; oxide of manganese, 8·52; sand, 11·37; phosphoric acid, 1·50; sulphuric acid, traces; water and organic matter, 16·02=100·00. Bog iron-ore may either be formed *in situ* from still water, or may be laid down by currents in lakes. Of the former mode of formation, a familiar illustration is furnished by the "moor-band pan" or hard ferruginous crust, which in boggy places and on some ill-drained land, forms at the bottom of the soil, on the top of a stiff and tolerably impervious subsoil. Abundant bog-iron or lake-ore is obtained from the bottoms of some lakes in Norway and Sweden. It forms everywhere on the

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[147] See Senft's work already (p. 250) cited, p. 168; also postea, Book III. Part II. Sect. iii.

shallower slopes near banks of reeds, where there is no strong current of water, occurring in granular concretions (Bohnerz) that vary from the size of grains of coarse gunpowder up to nodules 6 inches in diameter, and forming layers 10 to 200 yards long, 5 to 15 yards broad, and 8 to 30 inches thick. These deposits are worked during winter by inserting perforated iron shovels through holes cut in the ice; and so rapidly do they accumulate, that instances are known where, after having been completely removed, the ore at the end of twenty-six years was found to have gathered again to a thickness of several inches. A layer of loose earthy ochre 10 feet thick is believed to have formed in 600 years on the floor of the Lake Tisken near the old copper mine of Falun in Sweden.[148] According to Ehrenberg, the formation of bog-ore is due, not merely to the chemical actions arising from the decay of organic matter, but to a power possessed by diatoms of separating iron from water and depositing it as hydrous peroxide within their siliceous framework.

Aluminous Yellow Iron-Ore is closely related to the foregoing. It is a mixture of yellow or pale brown, hydrated peroxide of iron, with clay and sand, sometimes with silicate of iron, hydrated oxide of manganese, and carbonate of lime, and occurs in dull, usually pulverulent grains and nodules. Occasionally these nodules may be observed to consist of a shell of harder material, within which the yellow oxide becomes progressively softer toward the centre, which is sometimes quite empty. Such concretions are known as ætites or eagle-stones. This ore occurs in the Coal-measures of Saxony and Silesia, also in the Harz, Baden, Bavaria, etc., and among the Jurassic rocks in England.

Clay-Ironstone (Sphærosiderite) has been already (p. 143) referred to. It occurs abundantly in nodules and beds in the Carboniferous system in most parts of Europe. The nodules are generally oval and flattened in form, varying in size from a small bean up to concretions a foot or more in diameter, and with an internal system of radiating cracks, often filled with calcite (Fig. 26). In many cases, they contain in the centre some organic substance, such as a coprolite, fern, cone, shell, or fish, that has served as a surface round which the iron in

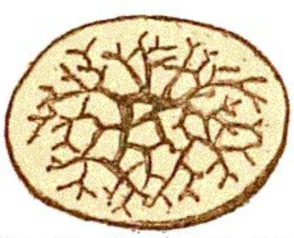

Fig. 26.—Septarian Nodule of Clay-ironstone.

[148] A. F. Thoreld, Geol. Fören. Förhand. Stockholm, iii. p. 20, postea, pp. 407, 483.

the water and the surrounding mud could be precipitated. Seams of clay-ironstone vary in thickness from mere paper-like partings up to beds several feet deep. The Cleveland seam in the middle Lias of Yorkshire is about 20 feet thick. In the Carboniferous system of Scotland certain seams known as *Black-band* contain from 10 to 52 per cent of coaly matter, and admit of being calcined with the addition of little or no fuel. They are sometimes crowded with organic remains, especially lamellibranchs (*Anthracosia*, *Anthracomya*, etc.) and fishes (*Rhizodus*, *Megalichthys*, etc.).

A microscopic examination of some black-band ironstones reveals a very perfect oolitic structure, showing that the iron has either replaced an original calcareous oolite or has been precipitated in water having such a gentle movement as to keep the granules quietly rolling along, while their successive concentric layers of carbonate were being deposited. Mr. Sorby has observed in the Cleveland ironstones an abnormal form of oolitic structure, and remarks that one specimen bore evidence that the iron, mostly in the form of small crystals of the carbonate, had been introduced subsequently to the formation of the rock, as it had replaced some of the aragonite of the inclosed shells.[149]

The subjoined analyses show the composition of some varieties of clay-ironstones.[150]

	Clay iron-ore (Coal measures), Yorkshire	Black-band (Carboniferous), Scotland	Cleveland ore (Lias), Yorkshire
Peroxide of iron	1·45	2·72	2·86
Protoxide of iron	36·14	40·77	43·02
Protoxide of manganese	1·38	—	0·40
Alumina	6·74	—	5·87
Lime	2·70	0·90	5·14 (zinc)
Magnesia	2·17	0·72	5·21
Potash	0·65	—	—
Silica	17·37	10·10	7·17
Carbonic acid	26·57	26·41	25·50
Phosphoric acid	0·34	—	1·81
Sulphuric acid	trace	—	—
Iron pyrites	0·10	—	—
Water	1·77	1·0	3·48
Organic matter	2·40	17·38	0·15
	99·78	100·00	100·61
Percentage of iron	29·12	34·60	35·46

[149] Address to Geol. Soc. February, 1879.

[150] See Percy's "Metallurgy," vol. ii. Bischof, "Chem. und Phys. Geol." supp. (1871), p. 65.

B. Crystalline, including Rocks formed from Chemical Precipitation

This division consists mainly of chemical deposits, but includes also some which, originally formed of organic calcareous débris, have acquired a crystalline structure. The rocks included in it occur as laminæ and beds, usually intercalated among clastic formations, such as sandstone and shale. Sometimes they attain a thickness of many thousand feet, with hardly any interstratification of mechanically derived sediment. They are being formed abundantly at the present time by mineral springs and on the floor of inland seas; while on the bottom of lakes and of the main ocean, calcareous organic accumulations are in progress, which will doubtless eventually acquire a thoroughly crystalline structure like that of many limestones.

Ice.—So large an area of the earth's surface is covered with ice, that this substance deserves notice among geological formations. Ice is commonly and conveniently classified in two divisions, snow-ice and water-ice, according as it results from the compression and alternate melting and freezing of fallen snow, or from the freezing of the surface or bottom of sheets of water.

Snow-ice (see Book III. Part II. Sect. ii. § 5) is of two kinds. 1st, Fallen snow on mountain slopes above the snow-line gradually assumes a granular structure. The little crystalline needles and stars of ice are melted and frozen into rounded granules which form a more or less compact mass known in Switzerland as *Névé* or *Firn*. 2d, When the granular névé slowly slides down into the valleys, it acquires a more compact crystalline structure and becomes *glacier-ice*. According to the researches of F. Klocke, glacier-ice is, throughout its mass, an irregular aggregate of distinct crystalline grains, the boundaries of which form the minute capillary fissures so often described.[161] Its structure thus closely corresponds to that of marble (p. 263).

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[161] Neues Jahrb. 1881 (i.), p. 23. Grad and Dupré (Ann. Club. Alp. Franc. (1874) show how the characteristic structure of glacier-ice may be revealed by allowing colored solutions to permeate it.

Glacier-ice in small fragments is white or colorless, and often shows innumerable fine bubbles of air, sometimes also fine particles of mud. In larger masses, it has a blue or green-blue tint, and displays a veined structure, consisting of parallel vertical veinings of white ice full of air-bubbles, and of blue. clear ice without air-bubbles. Snow-ice is formed above the snow-line, but may descend in glaciers far below it. It covers large areas of the more lofty mountains of the globe, even in tropical regions. Toward the poles it descends to the sea, where large pieces break off and float away as icebergs.

Water-ice (see Book III. Part II. Sect. ii. § 5) is formed, 1st, by the freezing of the surface of fresh water (river-ice, lake-ice), or of the sea (ice-foot, floe-ice, pack-ice); this is a compact, clear, white or greenish ice. 2d, by the freezing of the layer of water lying on the bottom of rivers, or the sea (bottom-ice, ground-ice, anchor-ice); this variety is more spongy, and often incloses mud, sand and stones.[152]

Rock-Salt (Sel gemme, Steinsalz, p. 144) occurs in layers or beds from less than an inch to many hundred feet in thickness. The salt deposits at Stassfurt, for example, are 1197 feet thick, of which the lowest beds comprise 685 feet of pure rock-salt, with thin layers of anhydrite ¼-inch thick dividing the salt at intervals of from one to eight inches. Still more massive are the accumulations of Sperenberg near Berlin, which have been bored through to a depth of 4200 feet, and those of Wieliczka in Gallicia which are here and there more than 4600 feet thick.

The more insoluble salts (notably gypsum or anhydrite) are apt to appear in the lower parts of a saliferous series. When purest, rock-salt is clear and colorless, but usually is colored red (peroxide of iron), sometimes green, or blue (chloride or silicate of copper). It varies in structure, being sometimes beautifully crystalline and giving a cubical cleavage; laminated, granular, or less frequently fibrous. It usually contains some admixture of clay, sand, anhydrite, bitumen, etc., and is often mixed with chlorides of magnesium, calcium, etc. In some places it is full of vesicles (not infrequently of cubic form) containing saline water; or it abounds with minute cavities filled with hydrogen, nitro-

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[152] On the properties of ice with some interesting geological bearings, see O. Pettersson, "Vega-Expeditionens Vetenskapliga Iakttagelser," vol. ii. p. 249, Stockholm, 1883.

gen, carbon-dioxide, or with some hydrocarbon gas. Occasionally remains of minute forms of vegetable and animal life, bituminous wood, corals, shells, crustaceans, and fish teeth are met with in it. Owing to its ready solubility, it is not found at the surface in moist climates. It has been formed by the evaporation of very saline water in inclosed basins—a process going on now in many salt-lakes (Great Salt Lake of Utah, Dead Sea), and on the surface of some deserts (Kirgis Steppe). In different parts of the world, deposits of salt have probably always been in progress from very early geological times. Saliferous formations of Tertiary and Secondary age are abundant in Europe, while in America they occur even in rocks as old as the Upper Silurian period, and among the Punjab Hills in still more ancient strata.[163]

Carnallite—a chloride of potassium and magnesium (p. 144). It occurs in a bed 20 to 30 metres thick which overlies the rock-salt in the saliferous series of Stassfurt, and has been found in other old salt deposits, as well as among the "salterns" or "salines" along the Mediterranean coast where the water of that inland sea is evaporated in the manufacture of salt. It so closely resembles rock-salt that it was formerly included with it, but it is much less frequently met with. It is a valuable source for the manufacture of potash-salts.

Limestone (Calcaire, Kalkstein)—essentially a mass of calcium-carbonate, sometimes nearly pure, and entirely or almost entirely soluble in hydrochloric acid, sometimes loaded with sand, clay, or other intermixture. Few rocks vary more in texture and composition. It may be a hard, close-grained mass, breaking with a splintery or conchoidal fracture; or a crystalline rock built up of fine crystalline grains of calcite, and resembling loaf-sugar in color and texture; or a dull earthy friable chalk-like deposit; or a compact, massive, finely-granular rock resembling a close-grained sandstone or freestone. As its hardness is about 3, it can easily be scratched with a knife and the white powder gives a copious effervescence with acid. The specific gravity naturally varies according to the impurity of the rock, ranging from 2·5 to 2·8. The colors, too, vary extensively, the most common being shades of blue-gray and cream-color passing into white. Some limestones are highly siliceous, the calcareous matter having been accompanied with silica

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[163] On salt deposits of various ages, see A. C. Ramsay, Brit. Assoc. Rep. 1880, p. 10; also Index, sub voc. "Salt Deposits."

in the act of deposition; others are argillaceous, sandy, ferruginous, dolomitic, or bituminous. By far the larger number of limestones are of organic origin; though owing to internal rearrangement, their original clastic character has frequently been changed into a crystalline one. Under the present subdivision are placed all those limestones which have had a distinctly chemical origin, and also those which though doubtless, in many cases, originally formed of organic débris, have lost their fragmental, and have assumed instead a crystalline structure. (For the organic limestones see p. 244.)

Compact, common limestone—a fine-grained crystalline-granular aggregate, occurring in beds or laminæ interstratified with other aqueous deposits. When purest it is readily soluble in acid with effervescence, leaving little or no residue. Many varieties occur, to some of which separate names are given. *Hydraulic limestone* contains 10 per cent or more of silica (and usually alumina) and, when burned and subsequently mixed with water, forms a cement or mortar, which has the property of "setting" or hardening under water. Limestones containing perhaps as much as 25 per cent of silica, alumina, iron, etc., that in themselves would be unsuitable for many of the ordinary purposes for which limestones are used, can be employed for making hydraulic mortar. These limestones occur in beds like those in the Lias of Lyme Regis, or in nodules like those of Sheppey, from which Roman cement is made. *Cementstone* is the name given to many pale dull ferruginous limestones, which contain an admixture of clay, and some of which can be profitably used for making hydraulic mortar or cement. *Fetid limestone* (*stinkstein*, *swinestone*) gives off a fetid smell (sulphuretted hydrogen gas), when struck with a hammer. In some cases, the rock seems to have been deposited by volcanic springs containing decomposable sulphides as well as lime. In other instances, the odor may be connected with the decomposition of imbedded organic matter. In some quarries in the Carboniferous Limestone of Ireland, as mentioned by Jukes, the freshly-broken rock may be smelled at a distance of a hundred yards when the men are at work, and occasionally the stench becomes so strong that the workmen are sickened by it, and require to leave off work for a time. *Cornstone* is an arenaceous or siliceous limestone particularly characteristic of some of the Palæozoic red sandstone formations. *Rottenstone* is a decomposed siliceous limestone from which most or all of the lime has been removed, leaving a siliceous skeleton of the rock. A similar decomposition takes place in some ferruginous limestones, with the result of leaving a yellow skeleton of ochre. Common limestone, having been deposited in water usually containing other substances in suspension or solution, is almost always mixed with impurities, and where the mixture is sufficiently distinct it receives a special name, such as siliceous limestone, sandy limestone, argillaceous limestone, bituminous limestone, dolomitic limestone.

Travertine (calcareous tufa, calc-sinter) is the porous material deposited by calcareous springs, usually white or yellowish, varying in texture from a soft chalk-like or marly substance to a compact building-stone. (See Book III. Part II. Sect. iii. §§ 3, 6.) *Stalactite* is the name given to the calcareous pendent deposit formed on the roofs of limestone-caverns, vaults, bridges, etc.; while the water, from which the hanging lime-icicles are derived, drips to the floor, and on further evaporation there, gives rise to the crust-like deposit known as *stalagmite*. Mr. Sorby has shown that in the calcareous deposits from fresh water there is a constant tendency toward the production of calcite crystals with the principal axis perpendicular to the surface of deposit. Where that surface is curved, there is a radiation or convergence of the fibre-like crystals, well seen in sections of stalactites and of some calcareous tufas (Fig. 108).

Oolite—a limestone formed wholly or in part of more or less perfectly spherical grains, and having somewhat the aspect of fish-roe. Each grain consists of successive concentric shells of carbonate of lime, frequently with an internal radiating fibrous structure, which gives a black cross between crossed Nicols (Fig. 27). The calcareous material was deposited round some minute particle of sand or other foreign body which was kept in motion, so that all sides could in turn become incrusted. Oolitic grains of this character are now forming in the springs of Carlsbad (Sprudelstein); but they may no doubt also be produced where gentle currents in lakes, or in partially inclosed areas of the sea, keep grains of sand or fragments of shells drifting along in water, which is so charged with lime as to be ready to deposit it upon any suitable surface. An oolitic limestone may contain much impurity. Where the calcareous granules are cemented in a somewhat argillaceous matrix the rock is known in Germany as Rogenstein. Where the individual grains of an oolitic limestone are as large as peas, the rock is called a pisolite (pea-grit). The granules sometimes consist of aragonite. Oolitic structure is found in limestones of all ages from Palæozoic down to recent times.[154] Mr. E. Wethered has recently pointed out that many oolitic grains show curious vermiform twistings in their outer concentric coats, which he regards as of organic origin, either plant or animal (*Girvanella*).[155] In some instances oolites have had their calcareous matter replaced by carbonate or oxide of iron, so as to become oolitic ironstones.

Marble (granular limestone)—a crystalline-granular aggregate composed of crystalline calcite-granules of remarkably uniform size, each of which has its own independent

Fig. 27.—Microscopic Structure of Oolitic Limestone, after Sorby. (Magnified 30 Diameters.)

Fig. 28.—Microscopic Structure of white Statuary Marble. (Magnified 50 Diameters.)

twin lamellæ (often giving interference colors) and cleavage lines. This characteristic structure is well displayed when a thin slice of ordinary statuary marble is placed under the microscope (Fig. 28). Typical marble is white, but the rock is also yellow, gray, blue, green, red, black, or streaked and mottled, as may be seen in the numerous kinds used for ornamental purposes. Its granular structure gives it a resemblance to loaf-sugar, whence the term "saccharoid" applied to it. Fine silvery scales of mica or talc may often

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[154] Oolitic structure is found even among the limestones of the Dalradian metamorphic series of Scotland (Islay) which may possibly be pre-Palæozoic.

[155] Geol. Mag. 1889, p. 196; Quart. Journ. Geol. Soc. xlvi. (1890), p. 270. Mr. C. Reid has suggested that these tubular bodies may be due to the deposit of lime round organic filaments (Algæ) like the calcareous incrustation formed round fibres of hemp in kettles and boilers.

be noticed even in the purest marble (*Cipolino*). Some crystalline limestones associated with gneiss and schist are peculiarly rich in minerals—mica, garnet, tremolite, actinolite, anthophyllite, zoisite, vesuvianite, pyroxenes, and many other species occurring there often in great abundance. These inclusions can be isolated by dissolving the surrounding rock in acid (*ante*, p. 157).

Marble is regarded by most geologists as a metamorphic rock, that is, one in which the calcium-carbonate, whether derived from an organic or inorganic source, has been entirely recrystallized *in situ*. In the course of this change the original clay, sand or other impurities of the rock have been also crystallized, and now appear as the crystalline silicates just referred to. Marble occurs in beds and large lenticular masses associated with crystalline schists on many different geological horizons. In Canada it occurs of Laurentian; in Scotland of Cambrian; in Utah of Upper Carboniferous; in Southern Europe of Triassic, Jurassic and Cretaceous age.

Dolomite (Magnesian Limestone) consists typically of a yellow or white, crystalline, massive aggregate of the mineral dolomite; but the relative proportions of the calcium and magnesium-carbonates vary indefinitely, so that every gradation can be found, from pure limestone without magnesium-carbonate up to pure dolomite containing 45·65 per cent of that carbonate. Ferrous carbonate is also of common occurrence in this rock. The texture of dolomite is usually distinctly crystalline, the individual crystals being occasionally so loosely held together that the rock readily crumbles into a crystalline sand. A fissured cavernous structure apparently due to a process of contraction during the process of "*dolomitization*," is of common occurrence: even in compact varieties, cellular spaces occur, lined with crystallized dolomite (Rauchwacke), the crystals of which are often hollow and sometimes inclose a kernel of calcite. Other varieties are built up of spherical, botryoidal and irregularly-shaped concretionary masses. Dolomite, in its more typical forms, is distinguishable from limestone by its greater hardness (3·5–4·5), higher specific gravity (2·8–2·95), and much less easy solubility in acid. It occurs sometimes in beds of original deposit, associated with gypsum, rock-salt and other results of the evaporation of saturated saline waters; it is also found replacing what was once ordinary limestone. The process by which carbonate of lime is replaced by carbonate of magnesia, is referred to in Book III. Part I. Sect. iv. § 2.[156] Dolomite sometimes forms picturesque mountain masses, as in the Dolomite Mountains of the Eastern Alps.

Gypsum—a fine granular to compact, sometimes fibrous or sparry aggregate of the mineral gypsum, having a hardness of only 1·5–2 (therefore scratched with the nail), and a specific gravity of about 2·32, and being unaffected by acids; hence readily distinguishable from limestone, which it occasionally resembles. It is normally white, but may be colored gray or brown by an admixture of clay or bitumen, or yellow and red by being stained with iron-oxide. It occurs in beds, lenticular intercalations and strings, usually associated with beds of red clay, rock-salt, or anhydrite, in formations of many various geological periods from Silurian (New York) down to recent times. The Triassic gypsum deposits of Thuringia, Hanover and the Harz have long been famous. One of them runs along the south flank of the Harz Mountains as a great band six miles long and reaching a height of sometimes 430 feet.

Gypsum furnishes a good illustration of the many different ways in which some mineral substances can originate. Thus it may be produced, 1st, as a chemical precipitate from solution in water, as when sea-water is evaporated; 2d, through the decomposition of sulphides and the action of the resultant sulphuric acid upon limestone; 3d, through the mutual decomposition of carbonate of lime and sulphates of iron, copper, magnesia, etc.; 4th, through the hydration of anhydrite; 5th, through the action of the sulphurous vapors and solutions of volcanic orifices upon limestone and calcareous rocks.[157] It is in the first of these ways that the thick beds of gypsum associated with rock-salt in many geological formations have been formed. The first mineral to appear in the evaporation of sea-water being gypsum, it has been precipitated on the floors of inland seas and saline lakes before the more soluble salts.

Anhydrite—the anhydrous variety of calcium-sulphate, occurs as a compact or granular, white, gray, bluish or reddish aggregate in saliferous deposits. It is less frequent than gypsum, from which it is distinguished by its much greater hardness (3–3·5) and into which it readily passes by

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[156] On the mineralogical nature of dolomite see O. Meyer, Z. Deutsch, Geol. Ges. xxxi. p. 445, Loretz, op. cit. xxx. p. 387, xxxi. p. 756. Renard, Bull. Acad. Roy. Belg. xlvii. (1879), No. 5.

[157] Roth. Chem. Geol. i. p. 553.

taking up 0·2625 of its weight of water.[158] It often occurs in thin seams or partings in rock-salt; but it also forms large hill-like masses, of which the external parts have been converted into gypsum.

Ironstone.—Under this general term are included various iron-ores in which the peroxide, protoxide, carbonate, etc., are mingled with clay and other impurities. They have generally been deposited as chemical precipitates on the bottoms of lakes, under marshy ground, or within fissures and cavities of rocks. Some iron-ores are associated with schistose and massive rocks; others are found with sandstones, shales, limestones and coals; while some occur in the form of mineral veins. Those which have resulted from the co-operation of organic agencies are described at p. 254.

Hæmatite (red iron-ore), a compact, fine-grained, earthy, or fibrous rock of a blood-red to brown-red color, but where most crystalline, steel-gray and splendent, with a distinct cherry-red streak. Consists of anhydrous ferric oxide, but usually is mixed with clay, sand, or other ingredient, in such varying proportions as to pass, by insensible gradations, into ferruginous clays, sands, quartz, or jasper. Occurs as beds, huge concretionary masses, and veins traversing crystalline rocks; sometimes, as in Westmoreland, filling up cavernous spaces in limestone. Is found occasionally in beds of an oolitic structure among stratified formations. Some at least of the oolitic or pisolitic ironstones have resulted from the conversion of original grains of calcite in ordinary oolites into carbonate of iron which on oxidation has become magnetite, hæmatite, or limonite.

Limonite (brown iron-ore), an earthy or ochreous, compact, fine-grained or fibrous rock, of an ochre-yellow to a dark brown color, distinguishable from hæmatite by being hydrous and giving a yellow streak. Occurs in beds and veins, sometimes as the result of the oxidation of ferrous carbonate; abundant on the floors of some lakes; commonly found under marshy soil where it forms a hard brown crust upon the impervious subsoil (*bog-iron-ore*). Found likewise in oolitic concretions sometimes as large as walnuts, consisting of concentric layers of impure limonite

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158 See G. Rose on formation of this rock in presence of a solution of chloride of sodium. Neues. Jahrb. Min. 1871, p. 932. Also Bischof, "Chem. und Phys. Geol." Suppl. (1871), p. 188.

with sand and clay (*Bohnerz*). (See p. 255 and Book III. Part II. Sect. iii. § 3.)

Spathic Iron-ore, a coarse or fine crystalline or dull compact aggregate of the mineral siderite or ferrous carbonate, usually with carbonates of calcium, manganese and magnesium; has a prevalent yellowish or brownish color, and when fresh, its rhombohedral cleavage-faces show a pearly lustre, which soon disappears as the surface is oxidized into limonite or hæmatite. Occurs in beds and veins, especially among older geological formations. The colossal Erzberg at Eisenerz in Styria, which rises more than 2700 feet above the valley, consists almost wholly of siderite.[159]

Clay-ironstone (Sphærosiderite), a dull brown or black, compact form of siderite, with a variable mixture of clay, and usually also of organic matter. Occurs in the Carboniferous and other formations, in the form either of nodules, where it has usually been deposited round some organic centre, or of beds interstratified with shales and coals. It is more properly described at p. 256, with the organically derived rocks.

Magnetic iron-ore, a granular to compact aggregate of magnetite, of a black color and streak, more or less perfect metallic lustre, and strong magnetism. Commonly contains admixtures of other minerals, notably of hæmatite, chrome-iron, titanic-iron, pyrites, chlorite, quartz, hornblende, garnet, epidote, felspar. Occurs in beds and enormous lenticular masses (Stöcke) among crystalline schists, likewise in segregation-veins of gabbros and other eruptive rocks; also occasionally in an oolitic form (probably as a pseudomorph after an original calcareous oolite) among Palæozoic rocks, as in the so-called "pisolitic iron-ore" of North Wales. Among the Scandinavian gneisses lies the iron mountain of Gellivara in Lulea-Lappmark, 17,000 feet long, 8500 feet broad, and 525 feet high.

Siliceous Sinter (Geyserite, Kieselsinter), the siliceous deposit made by hot springs, including varieties that are crumbling and earthy, compact and flinty, finely laminated and shaly, sometimes dull and opaque, sometimes translucent, with pearly or waxy lustre, and with chalcedonic alterations in the older parts. The deposit may occur as an incrustation round the orifices of eruption, rising into dome-shaped, botryoidal, coralloid, or columnar elevations, or investing leaves and stems of plants, shells, insects, etc.,

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[159] Zirkel, Lehrb. i. p. 345.

or hanging in pendent stalactites from cavernous spaces which are from time to time reached by the hot water. When purest, it is of snowy whiteness, but is often tinted yellow or flesh color. It consists of silica 84 to 91 per cent, with small proportions of alumina, ferric oxide, lime, magnesia, and alkali, and from 5 to 8 per cent of water. (See Book III. Part II. Sect. iii. § 3, par. 6.)

Flint and Chert have been already described among the rocks of organic origin (*ante*, p. 247). **Hornstone**, an excessively compact siliceous rock, usually of some dull dark tint, occurs in nodular masses or irregular bands and veins. The name has sometimes been applied to fine flinty forms of felsite. **Vein-Quartz** may be alluded to here as a substance which sometimes occurs in large masses. It is a massive form of quartz found filling veins (sometimes many yards broad) in crystalline and clastic rocks; more especially in metamorphic areas. (See Quartz Rocks, p. 310.)

Some of the other varieties of silica occurring in large masses may be classed as rocks. Such are Jasper, and Ferruginous Quartz. These, as well as common vein-quartz, occur as veins traversing both stratified and unstratified rocks; also as beds associated with the crystalline schists. With them may be grouped Lydian-Stone (*Lydite*, *Kieselschiefer*), a black or dark-colored, excessively compact, hard, infusible rock with splintery fracture, occurring in thin, sharply defined bands, split by cross joints into polygonal fragments, which are sometimes cemented by fine layers of quartz. It consists of an intimate mixture of silica with alumina, carbonaceous materials, and oxide of iron, and under the microscope shows minute quartz-granules with dark amorphous matter. It occurs in thin layers or bands in the Silurian and later Palæozoic formations interstratified with ordinary sandy and argillaceous strata. As these rocks have not been materially altered, the bands of Lydian-stone may be of original formation, though the extent to which they are often veined with quartz shows that they have, in many cases, been permeated by siliceous water since their deposit. The siliceous rocks due to the operations of plant and animal life are described on p. 247, also in Book III. Part II. Sect. iii. § 3.

Some originally clastic siliceous rocks have acquired a more or less crystalline structure from the action of thermal water or otherwise. One of the most marked varieties has been termed *Crystallized Sandstone* (see p. 232). Another variety, known as *Quartzite*, is a granular and compact aggregate of quartz, which will be described in connection with the schistose rocks among which it generally occurs (p. 311).

II. Massive—Eruptive—Igneous

Almost all the members of this important subdivision have been produced from within the crust of the earth, in a molten condition. Nearly all consist of two or more minerals. Considered from a chemical point of view, they may be described as mixtures, in different proportions, of silicates of alumina, magnesia, lime, potash, and soda, usually with magnetic iron and phosphate of lime. In one series, the silicic acid has not been more than enough to combine with the different bases; in another, it occurs in excess as free quartz. Taking this feature as a basis of arrangement, some petrographers have proposed to divide the rocks into an acid group, including such rocks as granite, quartz-porphyry and rhyolite, where the percentage of silica ranges from 60 to 75 or more, a basic group, typified by such rocks as basalt, where the proportion of silica is only about 50 per cent or less, and an intermediate group represented by the andesites with a proportion of silica ranging between that of the other two groups.[160]

In the vast majority of igneous rocks, the chief silicate is a felspar—the number of rocks where the felspar is represented by another silicate (as leucite or nepheline) being comparatively few and unimportant. As the felspars group themselves into two divisions, the monoclinic or orthoclase, and the triclinic or plagioclase, the former with, on the whole, a preponderance of silica; and as these minerals oc-

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[160] See a paper on the chemical relations of the eruptive rocks by Prof. Rosenbusch, Tschermak's Min. Mittheil. xi. (1889), p. 144, also the paper quoted in footnote (163) on p. 272, and a Memoir on "the origin of Igneous Rocks," by J. P. Iddings, Phil. Soc. Washington, 1892, p. 90.

cur under tolerably distinct and definite conditions, other petrographers divide the felspar-bearing Massive rocks into two series: (1) the Orthoclase rocks, having orthoclase as their chief silicate, and often with free silica in excess, and (2) the Plagioclase rocks, where the chief silicate is some species of triclinic felspar. The former series corresponds generally to the acid group above mentioned, while the plagioclase rocks are intermediate and basic. It has been objected to this arrangement that the so-called plagioclase felspars are in reality very distinct minerals, with proportions of silica, ranging from 43 to 69 per cent; soda from 0 to 12; and lime from 0 to 20.[161] In addition to the felspar-rocks, there must be noted those in which felspar is either wholly absent or sparingly present, and where the chief part in rock-making has been taken by nepheline, leucite, olivine, or serpentine.

From the point of view of internal structure, a classification based upon microscopic research has been adopted by other writers, who recognize three leading types of micro-structure—*Granular*, *Porphyritic* and *Glassy*, or *Holocrystalline*, *Hemi-crystalline* and *Vitreous*. MM. Fouqué and Michel-Lévy, pointing out that most eruptive rocks are the result of successive stages of crystallization, each recognizable by its own characters, show that two phases of consolidation are specially to be observed, the first (porphyritic) marked by the formation of large crystals (phenocrysts), which were often broken and corroded by mechanical and chemical action within the still unsolidified magma; the second by the formation of smaller crystals, crystallites, etc., which are molded round the older series. In some

[161] Dana, Amer. Journ. Sci. 1878, p. 432. The modern methods of separating the felspars remove some of the difficulty above referred to.

rocks the former, in others the latter of these two phases is alone present. Two leading types of structure are recognized by these authors among the eruptive rocks. 1. Granitoid, where the constituents are mainly those of the second epoch of consolidation, but where neither amorphous magma nor crystallites are to be seen. This structure includes three varieties, (*a*) the *granitoid* proper, having crystals of approximately equal size; (*b*) *pegmatoid*, where there has been a simultaneous crystallization and regular arrangement of two constituents; (*c*) *ophitic*, in which the felspars are ranged parallel to one of their crystalline faces, forming a kind of transition into microlitic rocks. 2. Trachytoid, distinguished by a more marked contrast between the crystals of the first and second consolidation, the usual presence of an amorphous magma, and the fluxion structure. Three varieties are named: (*a*) *petrosiliceous*, with trains and spherulites of a finely clouded substance characteristic of the more acid rocks; (*b*) *microlitic*, characterized by the abundance of microlites of felspars and other minerals; (*c*) *vitreous*, derived from the two foregoing varieties by the predominance of the amorphous paste.[162]

It is common to introduce a chronological element into the classification of the massive rocks and to divide them into an ancient (Palæozoic and Mesozoic) and modern (Tertiary and recent) series. Certain broad distinctions can doubtless be made between many ancient and modern eruptive rocks; but, for reasons already stated, it seems inexpedient, in the present state of our knowledge, to employ relative antiquity (which must be determined by a totally distinct branch of geological inquiry, and may be

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[162] "Minéralogie Micrographique," p. 150.

erroneously determined) as a basis of petrographical arrangement.[163]

In the following arrangement the threefold division first mentioned above is adopted, according to the relative abundance of silica: 1st, Acid; 2d, Intermediate; 3d, Basic. In each of these series there is a range of structure from completely crystalline to completely glassy. The holocrystalline rocks are as a rule the deep-seated representatives of each series, while the vitreous and semi-vitreous are those which have either been erupted to the surface or have been connected with volcanic rather than plutonic action. No system of classification yet proposed can avoid incongruities, and it must be remembered that the hard and fast lines of our nomenclature do not represent any really abrupt demarcations in nature. As one rock graduates into another, our terminology should be elastic, so as to include such transitional forms.

i. Acid Series

In this family the silicic acid has been in such excess as often to separate out in the form of free quartz. Sometimes, as in granite, it has not assumed a definitely crystallized form, but is molded round the other crystals as a later stage of consolidation. In other rocks (quartz-porphyry, etc.) it occurs as a product of earlier consolidation, and often assumes perfect crystallographic contours, occurring even in double pyramids. The texture of the rocks is (1) holocrystalline or crystalline-granular (granitoid), as typically developed in granite; (2) hemi-crystalline (porphyritic, trachytoid), as in quartz-porphyry or felsite; (3) vitreous, as in obsidian.

Granite.[164]—A thoroughly crystalline-granular admixture of

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[163] For a tabular arrangement of the massive (eruptive) rocks and critical remarks on their classification, see Rosenbusch, Neues Jahrb. 1882, ii. p. 1.

[164] On the structure of granite, see the manuals of Zirkel and Rosenbusch and the memoirs there cited; also Zirkel's "Microscop. Petrography," 1876, p. 39; Phillips, Q. J. Geol. Soc. xxxi. p. 330; xxxvi. p. 1. J. C. Ward, op. cit. p. 569; and xxxii. p. 1. King's "Systematic Geology" (vol. i. of Explor. 40th

quartz, felspar, and mica, in particles of tolerably uniform size (Figs. 15 and 29). The felspar is chiefly white or pink orthoclase, but triclinic felspars (oligoclase and albite) may often be observed in smaller quantity, frequently distinguishable by their fine striation and more waxy lustre. Microcline is not infrequent, as well as the intercrystallization of orthoclase and plagioclase (Perthite). The mica may be the potash (muscovite) variety, usually of a white silvery aspect, but more commonly biotite or other dark brown or black variety. The quartz may be observed to form a kind of paste or magma wrapping round the other ingredients. Only in cavities of the granite do the component minerals occur in independent well-formed crystals, and there too the accessory minerals (beryl, topaz, tourmaline, garnet, etc.) are chiefly found.

Fig. 29.—Holocrystalline Structure of Granite (magnified).

From a microscopic examination of granite, it was formerly inferred that the rock has a thoroughly crystalline structure, with no megascopic ground-mass, nor microscopic base of any kind between the crystals or crystalline individuals. More recent and exhaustive study of the subject, however, has led to the conclusion that though nothing like a vitreous, or even porphyritic, ground-mass can be detected, there is yet sometimes discernible an analogous kind of entirely crystalline magma, in which the crystals or crystalline débris of the rock are imbedded, and in which they are partially dissolved. Having regard to the relations between this magma and its inclosed minerals, M. Michel-Lévy has observed that microscopic examination points to a distinction between granites in which the quartz is more recent than the other constituents and has consolidated at once, and those in which there are remains of earlier bipyramidal quartz. He distinguishes these two series as—(A) Ancient granites, composed of black mica, hornblende, oligoclase, and orthoclase, forming a crystalline débris im-

Parallel), p. 111 *et seq.* Michel-Lévy, Bull. Soc. Géol. France, 3d ser. iii. p. 199. Rosenbusch, Zeitsch. Deutsch. Geol. Gesell. xxviii. (1876), p. 369. H. Möhl, Nyt. Mag. Nat. xxiii. p. 1 *et seq.* J. Lehmann, "Untersuchungen über die Entstehung der Altkrystallinischen Schiefergesteine," 1884, p. 3. W. J. Sollas, Trans. Roy. Irish Acad. xxix. Part xiv. (1891).

bedded in a more recent crystalline magma of orthoclase and quartz. (B) Porphyroid granites, generally finer in grain than the preceding, and further distinguished by the occurrence of bi-pyramidal crystals of quartz (which made their appearance between the old felspar and the recent orthoclase), and of a notable quantity of white mica (rare among the ancient granites) posterior in advent even to the more recent quartz.[165]

Among the component minerals of granite, the quartz presents special interest under the microscope. It is often found to be full of cavities containing liquid, sometimes in such numbers as to amount to a thousand millions in a cubic inch and to give a milky turbid aspect to the mineral. The liquid in these cavities appears usually to be water containing sodium and potassium chlorides, with sulphates of these metals and of calcium (p. 196).

The mean of eleven analyses of granites made by Dr. Haughton gave the following average composition: silica, 72·07; alumina, 14·81; peroxide of iron, 2·22; potash, 5·11; soda, 2·79; lime, 1·63; magnesia, 0·33; loss by ignition, 1·09; total, 100·05, with a mean specific gravity of 2·66.

Most large masses of granite present differences of texture in different parts of their area. Some of these variations depend on the relation of the mass to the surrounding rocks (Bk. IV. Pt. VII.). Others may occur in any portion of a granite boss, and have been produced by the circumstances in which the mass consolidated. Some granites are marked by the occurrence of the cavities above referred to where the individual minerals have had room to assume sharply defined crystalline forms. Many granites are apt to be traversed by veins, sometimes due to a segregation of the surrounding minerals in rents of the original pasty magma, sometimes to a protrusion of a less coarsely crystalline (micro-granitic, felsitic) material into the main rock (Fig. 30). Some of the more important of these varieties are distinguished by special names. Thus, where the component quartz and felspar have crystallized together so as to inclose each other and assume a tendency to an orientation of their longer axes in one general direction, as they are specially apt to do in segregation-veins, the rock is termed P e g m a t i t e.[166] One of the most interesting struc-

[165] Bull. Soc. Géol. France, 3d ser. iii. (1875), p. 199.

[166] For an admirable and exhaustive account of the Pegmatite veins, and their associated minerals in Southern Norway, see the great monograph by Prof. W. C. Brögger in Groth's Zeitsch. Krystallographie, xvi. (1890).

tural varieties is the form of pegmatite termed Graphic Granite, in which the orientation of the quartz and felspar is singularly well developed (Fig. 31). The quartz has assumed the shape of long imperfect columnar shells, placed parallel to each other and inclosed within the orthoclase, so that a transverse section bears some resemblance to Hebrew writing. The two minerals have crystallized together, with their principal axes parallel. This intergrowth seems to show that there could have been little or no internal move-

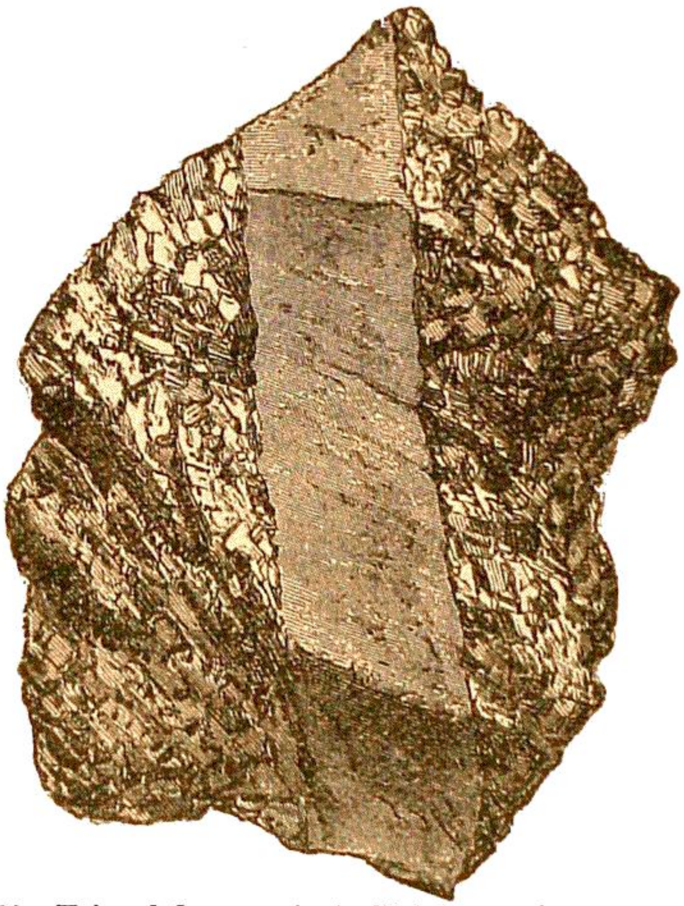

Fig. 30.—Vein of finer grain (aplite) traversing a coarsely crystalline Granite.

ment of the veins, in which it so frequently occurs, when the component minerals assumed their crystalline forms. Where the intergrowth is on a minute scale it is known as micropegmatite, and it forms the base of the rock to which the name of Granophyre has been given (Fig. 5). Here and there, an example may be found of a granite becoming fine-grained, but containing large scattered felspar crystals. Such a rock may be termed a *porphyritic granite*. Some granites abound in inclosed crystalline concretions or fragments. These are sometimes mere segregations of the materials of the granite, when they are usually ovoid in form and porphyritic in structure; in other cases, they are fragments of other rocks, and are then commonly schistose in structure and irregular in form.[167] In rare examples the component minerals of granite have crystallized with a radial concentric arrangement into rounded ball-like aggregates (spheroidal, orbicular granite).[168] In the centre, as well as round the edges of large bosses of granite, the minerals occasionally assume a more or less perfectly schistose

Fig. 31.—Graphic Granite (nat. size).

arrangement. When this takes place, the rock is called gneissose or gneiss granite. (See Book IV. Part VII.)

Differences in the proportions or nature of the component minerals have likewise suggested distinctive names. Of these the following are the more important: Granitite (biotite granite)—a mixture of pink orthoclase and abundant oligoclase, with a little quartz, some blackish green magnesia-mica, and occasionally with hornblende or augite. Hornblende-granite—a rock with hornblende added to the other normal constituents of granite, and usually poorer in quartz than normal granite. A well-known variety occurs at Syene in Upper Egypt, whence it was obtained anciently in large blocks for obelisks and other architectural works. The well-known Egyptian monoliths are made of it. It was called by Pliny "Syenite"—a name adopted by Werner as a general designation for horneblendic granites without quartz. The rock of Syene is really a hornblende-biotite-

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167 J. A. Phillips, Q. J. Geol. Soc. xxxvi. (1880), p. 1.

168 W. C. Brögger and H. Bäckström, Geol. Stockholm Förhandl. ix. (1887), p. 37. Hatch, Quart. Journ. Geol. Soc. xliv. (1888), p. 548, and authorities there cited.

granite. Augite-granite—a variety in which augite occurs with black mica. Tourmaline granite—a granitite with disseminated tourmaline. Greisen—a rare granitic rock from which the felspar has disappeared, found in some granite districts, especially in those wherein mineral-veins occur. Aplite—a fine-grained mixture of quartz and felspar, which have not infrequently intergrown (micropegmatite); found especially in veins in granite. "Elvan" is a Cornish term for a crystalline-granular mixture of quartz and orthoclase, forming veins which proceed from granite, or occur only in its neighborhood, and are evidently associated with it.[169] Under the name *Granulite* M. Michel-Lévy includes certain fine-grained granites with white mica, which to the naked eye appear to be composed entirely of felspar and quartz, or of felspar alone, though both mica and quartz appear in abundance when the rocks are microscopically examined. He includes in this category most of the rocks of the Alps described as "protogine."

Surrounding large masses of granite there are usually numerous veins, which consist of granite, quartz-porphyry, felsite, or sometimes even spherulitic material (Mull). There can be no doubt that these finer-grained protrusions really proceed from the crystalline granite mass. Lossen has shown that the Bode vein in the Harz has a granitoid centre, with compact porphyry sides, in which he found with the microscope a true glassy base.[170] Sometimes the rocks associated in this way with granite differ in composition from the main granite. Tourmaline is one of the characteristic minerals of granite-veins, though less observable in the main body of the rock; with quartz, it forms Schorl-rock.

Granite weathers chiefly by the decay of its felspars. These are converted into kaolin, the mica becomes yellow and soft, while the quartz stands out scarcely affected. The granite of the southwest of England has weathered to a depth of 50 feet and upward, so that it can be dug out with a spade, and is largely used as a source of porcelain-clay.

Granite occurs, (1) as an eruptive rock, forming huge bosses, which rise through other formations both stratified and unstratified, and sending out veins into the surrounding and overlying rocks, which usually show evidence of much alteration as they approach the granite; (2) connected with

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[169] J. A. Phillips, Q. J. Geol. Soc. xxxi. p. 334. Michel-Lévy, Bull. Soc. Géol. France, iii. 3d ser. p. 201.

[170] Zeitsch. Deutsch. Geol. Ges. xxvi. (1874), p. 856.

true volcanic rocks (as in the Tertiary granophyres of Mull and Skye), and forming, perhaps, the lower portions of masses which flowed out at the surface as lavas. Granite is thus a decidedly *plutonic* rock; that is, it has consolidated at some depth beneath the surface, and in this respect differs from the superficial *volcanic* rocks, such as lavas, which have flowed out above ground from volcanic orifices.

Quartz-Porphyry (Microgranite, Eurite).[171]—A fine-grained micrographic ground-mass, composed mainly of felspar and quartz, through which are usually scattered conspicuous porphyritic crystals of one or other or both of the same minerals.

To the naked eye the ground-mass varies from an exceedingly compact texture to one where abundant minute crystals can be detected. Of the porphyritic constituents the quartz occasionally occurs in bi-pyramidal crystals; the felspar is usually orthoclase, while black mica occasionally appears. Under the microscope the structure of the rock is found to be micrographic, with frequently a micropegmatitic arrangement of the quartz and felspar (granophyre).

The flesh-red quartz-porphyry of Dobritz, near Meissen, in Saxony, was found by Rentzsch to have the following chemical composition: Silica, 76·92; alumina, 12·89; potash, 4·27; soda, 0·68; lime, 0·68; magnesia, 0·68; oxide of iron, 1·15; water, 1·97; total, 99·54—specific gravity, 2·49.

The colors of the rock depend chiefly upon those of the felspar—pale flesh-red, reddish-brown, purple, yellow, bluish or slate-gray, passing into white, being in different places characteristic. It will be observed in this, as in other rocks containing much felspar, that the color, besides depending on the hue of that mineral, is greatly regulated by the nature and stage of decomposition. A rock, weathering externally with a pale yellow or white crust, may be found to be dark in the central undecayed portion. When the base is very compact, and the felspar-crystals well-defined and of a different color from the base, the rock, as it takes a good polish, may be used with effect as an ornamental stone. In popular language, such a stone is classed with the "marbles," under the name of "porphyry."

The Quartz-porphyries occur (1) with plutonic rocks, as eruptive bosses or veins, often associated with granite, from which, indeed, they may be seen to proceed directly;

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[171] Zirkel, "Microscop. Petrog." p. 71. See particularly Rosenbusch, "Mik. Phys." ii. p. 50.

of frequent occurrence also as veins and irregularly intruded masses among highly convoluted rocks, especially when these have been more or less metamorphosed; (2) in the chimneys of old volcanic orifices, forming there the "neck" or plug by which a vent is filled up; and (3) as bosses sometimes of large size which have been protruded in connection with volcanic action. Between the granophyres which are characterized by a micropegmatitic structure and the felsites or ancient rhyolites there is a close relation. Quartz-porphyries are abundant in Britain among formations of Lower Silurian, Old Red Sandstone and Lower Carboniferous age. In the Inner Hebrides they occur in large bosses or domes (granophyre) rising through the older Tertiary basaltic plateau.

Many of the rocks called "quartz-porphyry" are not micrographitic but have the "felsitic" structure arising from the devitrification of ancient forms of rhyolite (see p. 280).

Rhyolite[172] (Liparite, Quartz-trachyte)—a rock having a compact pale-gray, yellowish, greenish or reddish ground-mass, sometimes with glassy patches and layers, often showing perfect flow-structure, not infrequently also with spherulitic and perlitic structures, and with crystals of orthoclase (sanidine), granules of quartz and minute crystals of black mica, augite, more rarely hornblende. Considerable diversity exists in the texture of the rock. Frequently it is finely cavernous, the cavities being lined with chalcedony, quartz, amethyst, jasper, etc. Some varieties are coarse and granitoid in character. Intermediate varieties may be obtained like the quartz-porphyries, and these pass by degrees into more or less distinctly vitreous rocks. Throughout these gradations, however, which doubtless represent different stages in the crystallization of an original molten glass, a characteristic ground-mass can be seen under the microscope having a glassy, enamel-like, porcelaneous, microlitic character, with characteristic spherulitic and fluxion structures. In the quartz, glass-inclusions, having a dihexahedral form, may often be detected; but liquid inclusions are absent. An analysis by Vom Rath of a rhyolite from the Euganean Hills gave—silica, 76·03; alumina, 13·32; soda, 5·29; potash, 3·83; protoxide of iron, 1·74; magnesia, 0·30; lime, 0·85; loss, 0·32; total, 101·68—specific gravity, 2·553.

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[172] On rhyolite see Richthofen, Jahrb. K. K. Geol. Reichsanst. xi. 156. Zirkel, "Micro. Petrog." p. 163. King, "Explor. 40th Parallel," vol. i. p. 606.

The perlitic structure is so characteristic of this rock that the varieties which specially exhibit it were formerly regarded as a distinct rock-species under the name of *Perlite* or *Pearlstone*. As the name indicates, the structure presents enamel-like or vitreous globules which, occasionally assuming polygonal forms by mutual pressure, sometimes constitute the entire rock, their outer portions shading off into each other, so as to form a compact mass; in other cases, separated by and cemented in a compact glass or enamel. They consist of successive very thin shells, which, in a transverse section, are seen as coiled or spiral rings, usually full of the same kind of hair-like crystallites and crystals as in the more glassy parts of the rhyolite (Fig. 9). As these bodies both singly and in fluxion-streams traverse the globules, the latter may be regarded as a structure developed by contraction in the rock, during its consolidation, analogous to the concentric spheroidal structure seen in weathered basalt (Fig. 94). Among these concentrically laminated globules true spherulites occur, distinguished by their internal radiating fibrous structure (Figs. 7, 17).

Rhyolite is an acid rock of volcanic origin. It forms enormous masses in the heart of extinct volcanic districts in Europe (Hungary, Euganean Hills, Iceland, Lipari), and in North America (Wyoming, Utah, Idaho, Oregon, California).

Nevadite—a variety of rhyolite named by Richthofen from its development in Nevada, and characterized by its resemblance to granite, owing to the abundance of its porphyritic crystals, and the relatively small amount of ground-mass in which they are imbedded. The granitoid aspect is external only, as the ground-mass is distinct, and varies from a holocrystalline character to one with abundant glass, and the texture ranges from dense to porous.[173]

Felsite (Felstone).—Under this name a large series of rocks has been grouped which appear for the most part to have been originally vitreous lavas like the rhyolites, but which have undergone complete devitrification, though frequently retaining the perlitic, spherulitic, and flow-struc-

[173] Hague and Iddings, Amer. Journ. Sci. xxvii. (1884), p. 461. These authors distinguish between Nevadite and Liparite, the latter being characterized by the small number of porphyritic crystals imbedded in a relatively large amount of ground-mass, which, as in Nevadite, may be holocrystalline or glassy. They also distinguish *Lithoidal Rhyolite* and *Hyaline Rhyolite* as additional varieties.

tures. They vary in color from nearly white through shades of gray, blue and red or brown to nearly black, often weathering with a white crust. They are close-grained in texture, often breaking with a sub-conchoidal fracture and showing translucent edges. Porphyritic felspars (both orthoclase and plagioclase) and blebs of quartz are of frequent occurrence. The flow-structure is occasionally strongly marked by bands of different color and texture, sometimes curiously bent and curled over, indicating the direction of movement of the still unconsolidated rock. The spherulitic structure also may be found so strongly marked that the individual spherules measure an inch or more in diameter, so that the rock seems composed of an aggregate of balls, and was formerly mistaken for a conglomerate (*Pyromeride*).[174] Under the microscope many of the typical structures of rhyolite can be detected in felsites. The ground-mass of these rocks has given rise to much discussion, but it is now generally recognized as a more or less altered condition of the devitrification of an original vitreous mass (p. 207). Secondary changes have in large measure destroyed the original microlitic structure, but traces of it can often be found, while the spherulitic and perlitic forms frequently remain almost as fresh as in a recent rock. Felsites with a large proportion of alkalies, especially soda, have been called *Keratophyres*.[175]

Felsites have been found abundantly as interbedded lavas with tuffs and agglomerates associated with Silurian and older rocks in Wales and Shropshire.[176] Soda-felsites or keratophyres have been found to play a considerable part among the materials erupted by the Lower Silurian volcanoes of the southeast of Ireland.[177]

The **vitreous acid rocks** form an interesting group in which we may still detect what was probably the original condition

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[174] On nodular felsites see G. Cole, Quart. Journ. Geol. Soc. xli. (1885), p. 162; xlii. p. 183; Miss Raisin, op. cit. xlv. (1889), p. 247. Harker "Bala Volcanic Rocks," 1889, p. 28.

[175] Gümbel, "Palaeolit. Eruptivgest. Fichtelgebirg." (1874), p. 43. Rosenbusch, "Mikrosop. Physiog." ii. 434.

[176] Mr. Allport described some ancient forms of perlitic structure from Shropshire, in what were probably once ordinary rhyolites, Q. J. Geol. Soc. xxxiii. p. 449; and Mr. Rutley showed the presence of the same structure among the Lower Silurian lavas of North Wales. Op. cit. xxxv. p. 508.

[177] F. H. Hatch, Mem. Geol. Surv. Ireland, Explanation of Sheet 130; Geol. Mag. 1889, p. 70.

of at least the rhyolites and felsites. Every gradation can be traced from a perfect glass into a thoroughly devitrified and even crystalline rock. As already remarked, the original vitreous condition of rhyolite can still be seen even with the naked eye in the clots and streaks of glass that occasionally run through it in the direction of its flow-structure. Various names have been given to the glassy rocks, of which the chief are obsidian, pitchstone and pumice. These, however, are not to be regarded as distinct rock-species but rather as the glassy condition of different lavas.

Obsidian (rhyolite-glass)—the most perfect form of volcanic glass, externally resembling bottle glass, having a perfect conchoidal fracture, and breaking into sharp splinters, transparent at the edges. Its colors are black, brown, or grayish-green, rarely yellow, blue, or red, but not infrequently streaked or banded with paler and darker hues. A thin slice of obsidian prepared for the microscope is found to be very pale yellow, brown, gray, or nearly colorless, and on being magnified shows that the usual dark colors are almost always produced by the presence of minute opaque crystallites, which present themselves as black opaque trichytes, sometimes beautifully arranged in eddy-like lines showing the original fluid movement of the rock (Fig. 19); also as rod-like transparent microlites. They occasionally so increase in abundance as to make the rock lose the aspect of a glass and assume that of a dull flint-like or enamel-like stone. This devitrification can only be properly studied with the microscope. Again, dull gray enamel-like spherulites appear in some parts of the rock in great abundance, drawn out into layers so as to give the rock a fissile structure, while steam- or gas-cavities likewise occur, sometimes so large and abundant as to impart a cellular aspect. The occurrence of abundant sanidine crystals gives rise to *Porphyritic Obsidian*. Many obsidians, from the increase in the number of their steam-vesicles, pass into pumice. Now and then, the steam-pores are found in enormous numbers, of extremely minute size, as in an obsidian from Iceland, a plane of which, about one square millimetre in size, has been estimated to include 800,000 pores. The average chemical composition of obsidian is—silica, 71·0; alumina, 13·8; potash, 4·0; soda, 5·2; lime, 1·1; magnesia, 0·6; oxides of iron and manganese, 3·7; loss, 0·6 (little or no water). Mean specific gravity, 2·40. Obsidian occurs as a product of the volcanoes of late geological periods. It is found in Lipari, Iceland, and Teneriffe; in North America, it has been erupted from many points among the Western Territories;[178] it is met with also in New Zealand.

Pitchstone is a name given to the less perfectly glassy acid rocks, which are distinguished by a resinous or pitch-like lustre, and internally by a more advanced development of microlites than in obsidian. They thus represent a further stage of devitrification. These rocks are easily frangible, breaking with a somewhat splintery fracture, translucent on thin edges, with usually a black or dark green color, that ranges through shades of green, brown, and yellow to nearly white. Examined microscopically, they are found to consist of glass in which are diffused hair-like, feathery and rod-shaped microlites, or more definitely formed crystals of orthoclase, plagioclase, quartz, hornblende, augite, magnetite, etc. The pitchstone of Corriegills, in the island of Arran, presents abundant green, feathery, and dendritic microlites of hornblende (Fig. 14).[179] Occasionally, as in Arran, pitchstone assumes a spherulitic or perlitic structure. Sometimes it becomes porphyritic, by the development of abundant sanidine crystals (Isle of Eigg).

Pitchstone is found as (1) intrusive dikes, veins, or bosses, probably in close connection with former volcanic activity, as in the case of the dikes, which in Arran traverse Lower Carboniferous rocks, but are probably of Miocene age, and those which in Meissen send veins through and overspread the younger Palæozoic felsite-porphyries; (2) sheets which have flowed at the surface, as in the remarkable mass forming the Scuir of Eigg, which has filled up a river-channel of older Tertiary age.[180]

Pumice (Ponce, Bimstein)—a general term for the loose, spongy, cellular, filamentous or froth-like parts of lavas. So distinctive is this structure, that the term *pumiceous* has come into general use to describe it. There can be no doubt that this froth-like rock owes its peculiarity to the abundant escape of steam or gas through its mass while still in a state of fusion. The most perfect forms of pumice are found among the acid lavas, but this type of rock may be met with in the other groups. Microscopic examination of a rhyolitic pumice reveals a glass crowded with enormous

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178 For an account of the obsidian of the Yellowstone Park see J. P. Iddings, 7th Rept. U. S. Geol. Surv. (1885–86), p. 255; consult also Zirkel, "Microscop. Petrog."

179 See F. A. Gooch, Min. Mittheil. 1876, p. 185. Allport, Geol. Mag. 1881, p. 438.

180 Quart. Journ. Geol. Soc. (1871), p. 303.

numbers of minute gas- or vapor-cavities, usually drawn out in one direction, also abundant crystallites like those of obsidian. Owing to its porous nature, pumice possesses great buoyancy and readily floats on water, drifting on the ocean to distances of many hundreds of miles from land, until the cells are gradually filled with water, when the floating masses sink to the bottom.[181] Abundant rounded blocks of pumice were dredged up by the "Challenger" from the floor of the Atlantic and Pacific Oceans.

ii. Intermediate Series

In this series, the average percentage of silica is considerably less than in the acid series (56–66 per cent). Free quartz is not found as a marked constituent, although occasionally it occurs in some quantity, as microscopic examination has shown in the case even of some rocks where the mineral was formerly believed to be absent. A range of structure is displayed similar to that in the acid series. The thoroughly crystalline varieties are typified by syenite (and diorite), representing the granites of the acid rocks, those which possess a porphyritic ground-mass by orthoclase-porphyry, trachyte, and andesite, answering to quartz-porphyry and rhyolite, while the vitreous condition is represented among the trachytes and andesites by dark glasses of the obsidian and pitchstone types.

Syenite.—This name, formerly given in England to a granite with hornblende replacing mica, is now restricted to a rock consisting essentially of a holocrystalline mixture of orthoclase and hornblende, to which plagioclase, biotite, augite, magnetite, or quartz may be added. As already mentioned, the word, first used by Pliny in reference to the rock of Syene, was introduced by Werner as a scientific designation. It was applied by him to the rock of the Plauenscher-Grund, Dresden; he afterward, however, made that rock a greenstone. The base of all syenites, like that of granites, is thoroughly crystalline, without an amorphous ground-mass. The typical syenite of the Plauenscher-Grund, formerly described as a coarse-grained mixture of flesh-colored orthoclase and black hornblende, containing no quartz, and with no indication of plagioclase, was regarded as a normal orthoclase-hornblende rock. Micro-

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[181] On porosity, hydration, and flotation of pumice, see Bischof, "Chem. und Phys. Geol." suppl. (1871), p. 177.

scopical research has, however, shown that well-striated triclinic felspars, as well as quartz, occur in it. Its composition is: silica, 59·3; alumina, 16·85; protoxide of iron, 7·01; lime, 4·43; magnesia, 2·61; potash, 6·57; soda, 2·44; water, etc., 1·29; total, 101·03. Average specific gravity, 2·75 to 2·90.

Syenite is of much less frequent occurrence than granite. While always thoroughly granitic in structure, it varies in texture from coarse granular, where the individual minerals can readily be distinguished by the naked eye, to compact. Among its accessory minerals of common occurrence may be mentioned titanite (sphene), quartz, apatite, epidote, orthite, magnetite, pyrite, zircon. The predominance of one or more of the ingredients has given rise to the separation of a few varieties under distinctive names. In the typical syenite, the dark silicate is almost wholly hornblende; sometimes there are to be found traces of augite within the hornblende, indicating that the former mineral was the original constituent and has been changed by paramorphism. Where the ferro-magnesian silicate is mainly augite, as in the well-known rock of Monzoni, the rock is termed Augite-syenite or Monzonite; where brown mica predominates it gives rise to Mica-syneite or Minette.

Elaeolite-syenite (*Nepheline-syenite*) is a granitoid rock, characterized by the association of the variety of nepheline known as elaeolite with orthoclase, and with minor proportions of plagioclase, microcline, hornblende, augite, biotite, sodalite, zircon, and sphene. It is distinguished by the rare minerals, upward of fifty in number, which it contains, and in which some of the rarer elements are combined, such as thorium, yttrium, cerium, lanthanum, tantalum, niobium, zirconium, etc. It is typically developed in Southern Norway (Brevig, Laurvig). Where zircon enters as an abundant constituent the rock is known as Zircon-syenite. Foyaite is the name given to a hornblendic variety found at Mount Foya, Portugal; Miascite is a variety with abundant mica, found at Miask; Ditroite, containing sodalite, spinel, etc., occurs at Ditró in Transylvania.

Orthoclase-Porphyry (Micro-syenite, Quartzless-porphyry, Orthophyre) stands to the syenites in the same relation that quartz-porphyry or micro-granite does to the granites. It is composed of a compact micro-granitic ground-mass, with little or no free quartz, but through which are usually scattered numerous crystals of orthoclase, sometimes also a triclinic felspar, black hornblende and glancing scales of dark biotite. It contains from 55 to 65 per cent of silica, thus differing from quartz-porphyry and felsite in its smaller proportion of this acid. It is also rather more easily scratched with the knife, but except by chemical or microscopical analysis, it is often impossible to draw a distinction between this rock and its equivalents in the acid series.

Orthoclase-porphyry occurs in veins, dikes, and intrusive sheets. Probably many so-called "felstones," whether occurring as lavas or as intrusive masses among the older Palæozoic formations, are really orthoclase-porphyries. Some highly micaceous varieties have been called **Mica-trap**—a vague term under which have also been included Minettes, Micaceous Quartz-porphyries, etc. The name **Lamprophyre**, originally given by Gümbel to some mica-traps from the Fichtelgebirge, has been proposed by Rosenbusch as a general term for the Mica-traps, divisible into two groups—the Orthoclastic, or syenitic, where the felspar is orthoclase (Minettes), and the Plagioclastic or dioritic, where the felspar is a plagioclase variety (Kersantites).[182] The lamprophyres occur abundantly as dikes or veins of a fine-grained texture, and dull reddish to brownish color, among the older Palæozoic rocks of Britain.[183]

The orthoclase-porphyry of Pieve in the Vicentin was found by Von Lasaulx to have the following composition:—silica, 61·07; alumina, 18·56; peroxides of iron and manganese, 2·60; potash, 6·83; soda, 3·18; lime, 2·86; magnesia, 1·18; carbonic acid, 1·36; loss, 2·13—specific gravity, 2·59.[184]

Diorite.[185]—Under this name is comprehended a group of

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[182] The typical locality for these rocks is Kersanton in Brittany, where they are dark-green and remarkably durable. A singular vein of kersantite, 3 to 6½ feet broad, has been traced for nearly five miles in the Harz. Lossen, Zeitsch. Deutsch. Geol. Ges. xxxii. (1880) p. 445. Jahrb. Preuss. Geol. Landesanst. 1880. A. von Groddeck, op. cit. 1882. M. Koch, op. cit. 1886. Barrois, Assoc. Française (1880), p. 561; Ann. Soc. Géol. Nord, xiv. (1886), p. 31.

[183] For an account of the Lamprophyres of the classical district of the Plauenscher-Grund, see B. Doss, Tschermak's Mineral Mittheil. xi. (1889).

[184] Zeitsch. Deutsch. Geol. Ges. xxv. p. 320.

[185] On diorite, its structure and geological relations, consult the memoir on Belgian plutonic rocks by De la Vallée Poussin and A. Renard, Mém. Acad. Royale Belg. 1876; Behrens, Neues Jahrb. Min. 1871, p. 460; Zirkel, "Microscopical Petrog." p. 83. J. A. Phillips, Q. J. Geol. Soc. xxxii. p. 155, and xxxiv. p. 471—two valuable papers in which the constitution of some of the "green-

rocks, which, possessing a granitic structure, differ from the granites in their much smaller percentage of silica, and from the syenites in containing plagioclase instead of orthoclase as their chief constituent. They are sometimes divided into two sections, the quartz-diorites and the normal diorites. Many of these rocks were formerly included in the general division of "Greenstones."

Quartz-diorite—a holocrystalline mixture of plagioclase (oligoclase, less frequently labradorite) and quartz with some hornblende, augite, or mica. It outwardly resembles gray granite, and, indeed, includes many so-called granites. Its silica ranges up to 67 per cent. In *normal Diorite*, quartz is almost entirely absent; hornblende and black mica occur together in some varieties, while pyroxene characterizes others. Under the microscope a thoroughly crystalline structure is seen, and among the pyroxene-diorites the felspar and pyroxene are sometimes intergrown in ophitic aggregates. The average chemical composition of quartzless diorite is: silica, 54; alumina, 16–18; potash, 1·5–2·5; soda, 2–3; lime, 6–7·5; magnesia, 6·0; oxides of iron and manganese, 10–14; mean specific gravity, about 2·95.

Among the varieties of diorite, the following may be mentioned. *Corsite* (from Corsica)—a granitoid mixture of grayish-white plagioclase, blackish-green hornblende, and some quartz, which have grouped themselves into globular aggregations with an internal radial and concentric structure (*Orbicular diorite*, *Kugeldiorit*, *Napoleonite*—Fig. 8). *Tonalite* (from Monte Tonale, Tyrol)—a variety containing quartz, hornblende, and biotite in strongly contrasted colors. *Epidiorite*—a name given to ancient rocks which have originally been pyroxenic eruptive masses, but, by metamorphism, have acquired a crystalline rearrangement of their constituents, the pyroxene being changed into hornblende, often fibrous or actinolitic, the felspar becoming granular, and the whole rock having acquired a more or less distinct schistose structure. The dark intrusive sheets associated with the crystalline schists of the Scottish Highlands and the north of Ireland are largely epidiorites. Some of these rocks are quartziferous, but many of them belong to the basic series (see p. 1052).

As the granites pass into fine-grained quartz-porphyries,

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stones" of the older geologists is clearly worked out. Many of these ancient rocks are there shown to be forms of doleritic lava and the change of their original augite into hornblende is traced.

and the syenites into compact orthoclase-porphyries, so the diorites have their close-textured varieties, which are comprised under the general term Aphanite, divisible into *Quartz-aphanite* and *Normal-aphanite*. The general characteristic of these rocks is that the constituent minerals become so minute as to disappear from the naked eye. They are dark heavy close-grained masses. They merge into the basic diabases (p. 170).

Trachyte[186]—a term originally applied to modern volcanic rocks possessing a characteristic roughness (τραχύς) under the finger, is now restricted to a compact, usually pale, porphyritic, frequently cellular, rock, consisting essentially of sanidine, with more or less triclinic felspar, augite, hornblende, and biotite, sometimes with apatite, and tridymite. It is distinguished from rhyolite, or quartz-trachyte, by the absence of free quartz, and by the smaller proportion of vitreous or microlitic (micro-felsitic) ground-mass. The sanidine crystals present abundant steam-pores and glass-inclusions, as well as hornblende-microlites and magnetite. In some varieties, the ground-mass appears to be entirely composed of microlites; in others, minor degrees of devitrification can be traced, until the ground-mass passes into a glass (trachyte-glass, obsidian). The trachytes of Hungary have been grouped as *Augite-trachyte*, *Amphibole-trachyte* and *Biotite-trachyte*. Average composition of Trachyte—silica, 60·0–64·0; alumina, 17·0; protoxide and peroxide of iron, 6·0–8·0; magnesia, 1·0; lime, 3·5; soda, 4·0; potash, 2·0–2·5. Average specific gravity, 2·65.

Trachyte is an abundantly diffused lava of Tertiary and Post-tertiary date. It occurs in most of the volcanic districts of Europe (Siebengebirge, Nassau, Transylvania, Bay of Naples, Euganean Hills); in the Western Territories of the United States;[187] in New Zealand. It also occurs among the Carboniferous lavas of Scotland.

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[186] On trachyte, see Zirkel, "Micro. Petrog." p. 143. King in vol. i. of "Explor. 40th Parallel," p. 578. On the relative age and classification of Hungarian trachytes, Szabó, Zeitsch. Deutsch. Geol. Ges. xxix. p. 635, and "Compte rend. Congrès Internationale de Géologie" (1878), Paris, 1880. For the Scottish Carboniferous trachytes see Presidential Address to the Geological Society 1892, and F. H. Hatch, Trans. Roy. Soc. Edin. 1892.

[187] It would appear that much of what has been regarded as trachyte in Western America is andesite, consisting essentially of plagioclase, and not of sanidine. The normal trachytes are now described as hornblende-mica-andesites, and the augite-trachytes are hypersthene-augite-andesites, most of the rest being dacites, and some of them rhyolites. Hague and Iddings, Amer. Journ. Sci. xxvii. (1884), p. 456.

Domite (so named from the Puy-de-Dôme) is a porous loosely aggregated trachyte, having a microlitic groundmass, through which are dispersed tridymite, sanidine, much plagioclase, hornblende, magnetite, biotite, and specular iron. Soda-trachyte (Pantellerite) is a variety rich in oligoclase, found in Pantelleria.

Phonolite (Nepheline-trachyte, Clinkstone)[188]—a term suggested by the metallic ringing sound emitted by the fresh compact varieties when struck, is applied to a compact, gray or brown, quartzless mixture of sanidine and nepheline, with nosean, hauyne, leucite, pyroxene, hornblende, or mica. The rock is rather subject to decomposition, hence its fissures and cavities are frequently filled with zeolites. An average specimen gave on analysis—silica, 57·7; alumina, 20·6; potash, 6·0; soda, 7·0; lime, 1·5; magnesia, 0·5; oxides of iron and manganese, 3·5; loss by ignition, 3·2 per cent. The specific gravity may be taken as about 2·58. Phonolite is sometimes found splitting into thin slabs which can be used for roofing purposes. Occasionally it assumes a porphyritic texture from the presence of large crystals of sanidine or of hornblende. When the rock is partly decomposed and takes a somewhat porous texture, it resembles normal trachyte.

It is a thoroughly volcanic rock, and generally of Tertiary date. It occurs sometimes filling the pipes of volcanic orifices, sometimes as sheets which have been poured out in the form of lava-streams, and sometimes in dikes and veins, as in Bohemia and Auvergne. Some of the great bosses or eruptive vents connected with the trachyte lavas of the Carleton Hills, Haddingtonshire, have recently been determined by Dr. Hatch to be true phonolites.

With the phonolites may be classed Leucite-trachyte, or Leucite-phonolite, where the felspathoid is leucite instead of nepheline, and Nosean-trachyte (Nosean-phonolite), or Hauyne-trachyte (Hauyne-phonolite), with nosean or hauyne taking the place of the felspar of ordinary phonolite.

Andesite—a name originally given by Von Buch to some lavas found in the Andes, is now applied to a large series of rocks distinguished from the trachytes in that their felspar is plagioclase, and passing by the addition of olivine

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188 Boricky, "Petrograph. Stud. Phonolitgestein. Böhmens."—Archiv. Landesdurchforchung Böhmen, 1874. G. F. Föhr, "Die Phonolite des Hegau's," Verh. Phys. Med. Ges. Würzburg, xviii. (1883). F. H. Hatch, Trans. Roy. Soc. Edin. 1892.

into dolerite and basalt. In fresh examples they are dark gray, or even black rocks with a compact ground-mass, through which striated felspar prisms may generally be observed. They often assume cellular and porphyritic structures. At the one end of the series stand rocks containing free silica (Dacite), while at the other are basalt-like masses of much more basic composition (Aguite-andesite). Under the microscope the ground-mass presents more or less of a pale brownish glass with abundant felspar microlites.

Dacite (Quartz-andesite)—composed mainly of plagioclase, quartz, and mica, with a varying amount of sanidine as an accessory constituent, and, by addition of hornblende and pyroxene, graduating into hornblende-andesite. The ground-mass has a felsitic, sometimes spherulitic, glassy, or finely granular base. Composition: silica, 69·36; alumina, 16·23; iron oxides, 2·41; lime, 3·17; magnesia, 1·34; alkalies, 7·08; water, 0·45. Mean specific gravity, 2·60. This rock is extensively developed in the Great Basin and other tracts of western North America among Tertiary and recent volcanic outbursts.

Hornblende-andesite[189] consists of a triclinic felspar (usually oligoclase), with hornblende, augite, or mica. The ground-mass resembles that of trachyte, presenting sometimes remains of a pale glass. The porphyritic minerals frequently show evidence of having been much corroded before consolidation. Composition: silica, 61·12; alumina, 11·61; oxides of iron, 11·64; lime, 4·33; magnesia, 0·61; potash, 3·52; soda, 3·85; ignition, 4·35. Hornblende-andesite is a volcanic rock of Tertiary and post-Tertiary date found in Hungary, Transylvania, Siebengebirge, and in some of the Western Territories of the United States. According to researches by Messrs. Hague and Iddings, gradations from this rock into basalt and hypersthene-andesite can be traced in California, Oregon, and Washington. These rocks, therefore, cannot be said to have sharply defined and distinct forms.[190] Under the name of Hornblende-mica-andesite American petrographers have described a frequent variety of rock throughout the Great Basin, characterized by the vitreous appearance of its felspar, its rough porous trachyte-like ground-mass, and the presence of mica

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[189] See Zirkel, "Microscop. Petrog." p. 122. King, in vol. i. of "Explor. 40th Parallel," p. 562. Hague and Iddings, Amer. Journ. Sci. xxvi. (1883), p. 230.

[190] Amer. Journ. Sci. Sept. 1883, p. 233.

as an essential constituent. This term will include a large proportion of the rocks hitherto classed as trachytes, but in which the felspar proves to be plagioclase and not sanidine.[191]

Pyroxene-andesite—consisting of labradorite or oligoclase, with augite (less frequently a rhombic pyroxene) and abundant magnetite, sometimes with hornblende or mica, forming a dark heavy basalt-like compound, with a compact sometimes more or less distinctly vitreous groundmass. Composition: silica, 57·15; alumina, 16·10; protoxide of iron, 13·0; lime, 5·75; magnesia, 2·21; potash, 1·81; soda, 3·88. Mean specific gravity, 2·75–2·85.

It was formerly supposed that the pyroxene of the andesites was always augite. But rhombic forms of the mineral have now been frequently detected. Under the name of Hypersthene-andesite, certain Tertiary or recent rocks, stretching over vast areas in Western America, have been described as associated with other andesites and basalts. They are black to gray, or reddish-gray, in color, and vary in texture from dense, thoroughly crystalline forms, to others approaching white glassy pumice, the base under the microscope ranging from a brown glass to a holocrystalline structure. The magnesian silicate is pyroxene, chiefly in the orthorhombic form as hypersthene, but partly also augite. An analysis of the pumiceous form of the rock gave 62 per cent of silica, while the percentage of the same constituent in the glass of the base was found to rise to 69.94.[192]

Pyroxene-andesite occurs in dikes, lava-streams, plateaus, sheets, and neck-like bosses in regions of extinct and active volcanoes, as in the Inner Hebrides, Antrim, Transylvania, Hungary, Santorin, Iceland, Teneriffe, the Western Territories of North America, the Andes, New Zealand, etc. Many of the rocks of these regions now classed under this name have long been known and described as dolerites and basalts. Indeed, there is the closest relation between them and the true olivine-bearing dolerites and basalts. The latter occur among the Tertiary volcanic plateaus of Britain, interstratified with rocks which, not containing olivine, have been placed among the andesites. Neither in their mode of occurrence nor to the eye in hand specimens is there any

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[191] Hague and Iddings, Amer. Journ. Sci. xxvii. (1884), p. 460.

[192] Whitman Cross, Bull. U. S. Geol. Survey, 1883, No. 1. Hague and Iddings, Amer. Journ. Sci. xxvi. (1883), p. 226; xxvii. (1884), p. 457.

good distinction to be drawn between them. Under the name of Tholeite some interesting augite-andesites have been described, in which the felspar prisms form a network filled in with granular augite and interstitial matter (intersertal structure). In other varieties of andesite the felspar-mesh has been filled with large crystalline patches of augite, which thus incloses the felspar (ophitic structure).

Tephrite (Nepheline-andesite, Leucite-andesite, Nosean- or Hauyne-andesite)—a group of andesites, in which the felspar is partly replaced by one of the felspathoids, nepheline, leucite, nosean, or hauyne.

Porphyrite—a name for old forms of andesite which have generally undergone considerable alteration, and consequently appear as dull, sometimes earthy, generally reddish or brownish rocks. When fresh they are dark gray or black. They are commonly porphyritic, and show abundant scattered crystals of plagioclase, less commonly of mica. Their texture varies from coarse crystalline to exceedingly close-grained, passing occasionally into vitreous varieties (Yetholm, Cheviot Hills). Rocks of this type have been abundantly poured forth as lavas during Palæozoic time, and they occur as interstratified lava-beds, eruptive sheets, dikes, veins, and irregular bosses. In Scotland they form masses, several thousand feet thick, erupted in the time of the Lower Old Red Sandstone, and others of wide extent and several hundred feet in depth belonging to the Lower Carboniferous period. In Germany porphyrites appear also at numerous points among formations of later Palæozoic age.

Propylite—a name given by Richthofen to certain Tertiary volcanic rocks of Hungary, Transylvania, and the Western Territories of the United States, consisting of a triclinic felspar and hornblende in a fine-grained non-vitreous ground-mass, and closely related to the Hornblende-andesites. Their distinguishing feature is the great alteration which they have undergone, whereby their ferro-magnesian constituents have been converted into chlorite, and their felspars into epidote. Some quartziferous propylites have been described by Zirkel from Nevada, wherein the quartz abounds in liquid inclusions containing briskly-moving bubbles, and sometimes double inclosures with an interior of liquid carbon-dioxide.[193] A specimen from Storm

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[193] Zirkel's "Microscopical Petrography," p. 110. King, "Exploration of 40th Parallel," vol. i. p. 545. C. E. Dutton's "High Plateaus of Utah" (U. S.

Canon, Fish Creek Mountains, contained silica, 60·58; alumina, 17·52; ferric oxide, 2·77; ferrous oxide, 2·53; manganese, a trace; lime, 3·78; magnesia, 2·76; soda, 3·30; potash, 4·46; carbonic acid, a trace. Loss by ignition, 2·25; specific gravity, 2·6–2·7. The geologists of the Geological Survey of the United States believe that the rocks included under the term "propylite" in the western parts of America represent various stages of the decomposition of granular diorite, porphyritic diorite, diabase, quartz-porphyry, hornblende-andesite, and augite-andesite.[194] The name has been more recently applied by Rosenbusch to rocks which have undergone alteration by solfataric action.

iii. Basic Series

This third series of eruptive rocks is distinguished by its low silica percentage, and the relative abundance of its basic constituents. A similar range of structure can be traced in it as in the other two series. At the one extreme come rocks with a holocrystalline structure like the gabbros. These pass into others of a hemi-crystalline character, where, amid abundant crystals, crystallites, and microlites, there are still traces of the original glass. At the other end lie true basic volcanic glasses, which externally might be mistaken for the pitchstones and obsidians of the acid rocks.

Gabbro[195] (Euphotide)—a group of coarsely crystalline rocks composed of plagioclase (labradorite) or anorthite, magnetite or titaniferous iron, and some ferro-magnesian mineral, which in the normal gabbros is augite or diallage, but may be a rhombic pyroxene, hornblende, olivine, or mica. These minerals occur in allotriomorphic forms, as in granite; but they sometimes assume ophitic relations which lead into the rock termed dolerite. The felspar has often lost its vitreous lustre and passed into the dull opaque condition known as saussurite. The augite is usually in the form of diallage, distinguished by its schiller-spar lustre.

Geographical and Geological Survey of the Rocky Mountains), chaps. iii. and iv. Hague and Iddings, Amer. Journ. Sci. 1883.

[194] G. F. Becker on the Comstock Lode. Reports of U. S. Geological Survey 1880–81, and his full memoir in vol. iii. of the Monographs of U. S. Geol. Survey (1882). Hague and Iddings, Amer. Journ. Sci. xxvii. (1884), p. 454.

[195] On Gabbro see Lossen, Z. Deutsch. Geol. Ges. xix. p. 651. Lang, op. cit. xxxi. p. 484. Zirkel on Gabbros of Scotland, op. cit. xxiii. 1871. Judd, Quart. Journ. Geol. Soc. xlii. (1886), p. 49. G. H. Williams, Bull. U. S. Geol. Surv. No. 28 (1886). F. D. Chester, op. cit. No. 59 (1890). M. E. Wadsworth, Geol. Surv. Minnesota, Bull. 2, 1887.

Gabbro occurs as an eruptive rock among the older formations, likewise in large bosses and dikes in volcanic cores of Tertiary age (Mull, Skye). Average composition: silica, 49; alumina, 15; lime, 9·5; magnesia, 9·7; oxides of iron and manganese, 11·5; potash, 0·3; soda, 2·5. Loss by ignition, 2·5; specific gravity, 2·85–3·10.

The following varieties may be noticed: Olivine-gabbro—a granitoid or ophitic compound of plagioclase, augite, olivine, and magnetic or titaniferous iron; good examples are found among the deep-seated parts of some of the Tertiary volcanic vents of the Inner Hebrides. Hypersthene-gabbro or Norite (Hypersthenite, Hyperite, Schillerfels)—with a rhombic pyroxene in addition to or in place of the augite. Troctolite (Forellenstein)—a mixture of white anorthite with dark-green olivine, receives its name from the supposed resemblance of its speckled appearance to that of the side of a trout. Pyroxene-granulite (granular diorite, trap-granulite)—consisting of plagioclase, pyroxene (monoclinic and rhombic), hornblende, and garnet, distinguished by the granular condition of these minerals, and found among gneisses and other schistose rocks; this is probably an altered condition of some original pyroxenic eruptive rock.

Dolerite—an important group of basic rocks, which connect the gabbros with the basalts and include many of the rocks once termed "Greenstones." They are composed of labradorite (or anorthite), with some ferro-magnesian mineral (augite, enstatite, olivine, or mica) and magnetic or titaniferous iron. As a rule, they are holocrystalline, the constituent felspar and pyroxene or olivine being characteristically grouped in ophitic structure, but a little residual glass may occasionally be detected. They occur in bosses, intrusive sheets, and dikes, especially as the subterranean accompaniments of the volcanic action which has thrown out augite-andesites and basalts to the surface.

Normal or ordinary dolerite consists of plagioclase and augite, with magnetite or titanic iron and frequently olivine. Average composition: silica, 45–55; alumina, 12–16; lime, 7–13; magnesia, 3–9; oxides of iron and manganese, 9–18; potash, 0·1; soda, 2–5. Loss by ignition (water, etc.), 0·5–3; specific gravity, 2·75–2·96.

Different names have been proposed for the chief varieties. The most important of these are Olivine-dolerite—a dark, heavy, close-grained finely-crystalline rock, with scattered olivine, apt to weather with a brown curst. Olivine-free dolerite—a similar rock but containing no olivine. Enstatite-dolerite contains enstatite in addition to the other ingredients. Nepheline-dolerite, has the felspar largely or entirely replaced by nepheline (see Nephelinite, p. 299).

As varieties of dolerite depending for their peculiarities mainly upon their antiquity and the consequent alteration they have undergone, we may include the rocks comprehended under the term Diabase.[196] This name was given to certain dark green or black eruptive rocks found in older geological formations, and consisting essentially of triclinic felspar, augite, magnetite or titaniferous iron, apatite, sometimes olivine, usually with more or less of diffused greenish chloritic substances (viridite) which have resulted from the alteration of the augite or olivine. The average composition of typical diabase may be taken to be: silica, 48–50; alumina, 16·0; protoxide of iron, 12–15; lime, 5–11; magnesia, 4–6; potash, 0·8–1·5; soda, 3–4·5; water, 1·5–2. Specific gravity about 2·9. There is generally carbonic acid present, united with some of the lime as a decomposition product. As in ordinary dolerite, gradations may be traced from coarsely crystalline diabase[197] into exceedingly fine-grained and compact varieties (Diabase-aphanite), which sometimes assume a fissile character (Diabase-schiefer) where they have been subjected to crushing or cleavage. Some kinds present a porphyritic structure, and show dispersed crystals of the component minerals (Diabase-porphyry, Labrador-porphyry, Augite-porphyry); or, as in some varieties of diorite, a concretionary arrangement is produced by the appearance of abundant pea-like bodies of a compact felsitic material, imbedded in a compact or finely crystalline ground-mass (Variolite). When the green compact ground-mass contains small kernels of carbonate of lime, sometimes in great numbers, it is called Calcareous aphanite or Calcaphanite. Sometimes the rock is abundantly amygdaloidal. Though, as a rule, free silica does not occur in it, some varieties found to contain this mineral, possibly a secondary product, have been distinguished as Quartz-diabase. The presence of olivine has suggested the name Olivine-

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[196] The student will find in the Zeitschrift. Deutsch. Geol. Ges. 1874, p. 1, an important memoir by Dathe on the composition and structure of diabase. See also Zirkel's "Microscop. Petrog." p. 97.

[197] Michel-Lévy. Bull. Soc. Géol. France, 3d ser. xi. p. 282. Geikie, Trans. Roy. Soc. Edin. xxix. p. 487.

diabase as distinguished from the normal kinds in which this mineral is absent. A variety containing hornblende is termed Proterobase. Ophite, a variety occurring in the Pyrenees, contains diallage and epidote (see p. 212).

Diabase occurs both in contemporaneous beds and in intrusive dikes and sheets.

Basalt[198]—a black, extremely compact, apparently homogeneous rock, which breaks with a splintery or conchoidal fracture, and in which the component minerals can only be observed with the microscope, unless where they are scattered porphyritically through the mass (Fig. 32). The minerals consist of plagioclase (labradorite or anorthite), pyroxene (usually augite, but occasionally a rhombic form), olivine, magnetite or titaniferous iron. Many years ago, Andrews detected native iron in the basalt of Antrim, and more recently Nordenskiöld found this substance abundantly diffused in the basalt of Disco Island, occurring even in large blocks like meteorites (*ante*, p. 125). The groundmass of basalt presents under the microscope traces of glass in which are imbedded minute granules, hairs, needles, and microlites of felspar and augite. The proportion of this base varies within wide limits, insomuch that while in some parts of a basalt it so preponderates that the individual crystals are scattered widely through it, or are drawn out into beautiful streaks and eddies of fluxion structure, in others it almost disappears, and the rock then appears as a nearly crystalline mass, which thus graduates into dolerite and basic andesite. The component minerals frequently appear porphyritically dispersed, especially the olivine, the pale yellow grains of which are characteristic.

Fig. 32.—Microscopic Structure of Basalt (magnified). The large shaded crystals are Olivine considerably serpentinized: the numerous small white prisms are Plagioclase. A few Augite prisms occur which, to the right of the centre of the drawing, are aggregated into a large compound crystal. The black specks are Magnetite.

[198] On basalt rocks see Zirkel's "Basaltgesteine," 1870. Boricky's "Petrographische Studien en den Basaltgesteinen Böhmens," in Archiv für Naturwiss. Landesdurchforschung von Böhmen, ii. 1873. Allport, Q. J. Geol. Soc. xxx. p. 529. Geikie, Trans. Roy. Soc. Edin. xxix. Möhl, Nov. Act. Acad. Leop. Carol. xxxvi. (1873), p. 74; Neues Jahrb. 1873, pp. 449, 824. F. Eichstadt on Basalts of Scania, Sveriges Geol. Undersök, ser. c. No. 51, 1882. E. Svedmark, op. cit. No. 60, 1883.

Two types of basalt have been recognized in the great basaltic outbursts of Western America: (1) the porphyritic, consisting of a glassy and microlitic or micro-crystalline ground-mass, bearing relatively large crystals of olivine, felspar, and occasionally augite, a structure showing close relations to that of many andesites; (2) the granular (in the sense in which that term is used by Rosenbusch, *ante*, p. 177)—an aggregate of quite uniform grains, composed of well-developed plagioclase and olivine crystals, with ill-defined patches of augite, and frequently with a considerable amount of glass-base. By diminution of olivine and augmentation of silica, and the appearance of hypersthene, gradations can be traced from true olivine-basalts into normal andesites. Basalts with free quartz are not infrequent in Western America.[199]

Basalt occurs in amorphous and columnar sheets, which may alternate with each other or with associated tuffs. It also forms abundant dikes, veins, and intrusive bosses. It frequently assumes a cellular structure, which becomes amygdaloidal by the deposit of calcite, zeolites, or other minerals in the vesicles. A relation may be traced between the development of amygdales and the state of the rock; the more amygdaloidal the rock, the more is it decomposed, showing that the amygdales have probably in large measure been derived by infiltrating water from the basalt itself.

Vitreous Basalt (Basalt-glass, Tachylyte, Hyalomelan).[200]—Basalt passes into a condition which, even to the naked eye, is recognizable as that of a true glass. This more especially takes place along the edges of dikes and intrusive sheets. Where an external skin of the original molten rock has rapidly cooled and consolidated, in contact with the rocks through which the eruption took place, a transition can be traced within the space of less than a quarter of an inch from a crystalline dolerite, anamesite, basalt, or andesite into a black glass, which under the microscope assumes a pale brown or yellowish color, and is isotropic, but generally contains abundant microlites, sometimes with a globular or spherulitic concretionary structure. In such cases it seems indisputable that this glass represents what

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199 Hague and Iddings, Amer. Journ. Sci. xxvii. (1884), p. 456. Iddings, op. cit. xxxvi. (1888), p. 208, Bull. U. S. Geol. Surv. Nos. 66 and 79 (J. S. Diller).

200 See Judd & Cole, Q. J. Geol. Soc. xxxix. (1883), p. 444. Cole, op. cit. xliv. (1888), p. 300. Cohen, Neues Jahrb. 1876, p. 744; 1880 (vol. ii.), p. 23 (Sandwich Islands).

was the general condition of the whole molten mass at the time of eruption, and that the present crystalline structure of the rock was developed during cooling and consolidation. The glassy forms of basalt undergo alteration into a yellowish substance called Palagonite (p. 242). It is worthy of remark that in the analyses of vitreous basalts, the percentage of silica rises usually above, while their specific gravity falls below, that of ordinary crystalline basalt.

The average composition of basalt is—silica, 45–55; alumina, 10–18; lime, 7–14; magnesia, 3–10; oxides of iron and manganese, 9–16; potash, 0·5–3; soda, 2–5. Loss by ignition (water, etc.), 1–5; specific gravity, 2·85–3·10.

The basalt-rocks are thoroughly volcanic in origin, appearing in lava-streams, plateaus, sills, necks, dikes, and veins. The columnar structure is so common among the finer-grained varieties that the term "basaltic" has been popularly used to denote it. As already stated, it has been assumed by some writers that basalt did not begin to be erupted until the Tertiary period. But true basalt occurs abundantly in Scotland as a product of Lower Carboniferous volcanoes, and exhibits there a variety of types of minute structure.[201]

Basic Pumice.—Though the acid lavas furnish most of the pumice with which we are familiar, some of the basic kinds also assume a similar structure. Thus at Hawaii, the basic pyroxenic or olivine lavas give rise to a pumiceous froth.

Melaphyre—a name originally proposed by Brongniart and subsequently applied in various senses by different writers to include rocks which range in structure and composition from the more basic andesites to true olivine-basalts. The melaphyres for the most part belong to pre-Tertiary eruptions (though some Tertiary lavas have been described as melaphyre) and have undergone more or less alteration. If the word is to be retained as a definite rock-name it should be restricted to an altered type, as is now generally agreed, and preferentially to the older altered basalts. The melaphyres will then bear somewhat the same relation to the basalts that the diabases do to the dolerites and the porphyrites to the andesites. But it must necessarily happen that difficulty will be experienced in deciding which of the three

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[201] See Trans. Roy. Soc. Edin. xxix. (1879), p. 437, and Presidential Address, Quart. Journ. Geol. Soc. (1892), p. 129, where the types of microscopic structure observed by Dr. Hatch are enumerated.

names would be best applied to some of the eruptive rocks of the older geological formations. The melaphyres, as thus defined, are somewhat dull, dark brown, reddish, or green rocks, often amygdaloidal and showing their porphyritic minerals in an altered condition, the olivines especially being changed into serpentine or replaced by magnetite or even by hæmatite.[202]

Nepheline-basalt (Nepheline-Basanite). — Zirkel proved that certain black heavy rocks, having externally the aspect of ordinary basalt, contain little or no felspar, the part of that mineral being taken in some by nepheline, in others by leucite.[203] They are volcanic masses of late Tertiary age, but occur much more sparingly than the true basalts. They are found in the Odenwald, Thuringer Wald, Erzgebirge, Baden, etc. Mean composition—silica, 45·52; alumina, 16·50; ferric and ferrous oxides, 11·20; lime, 10·62; magnesia, 4·35; potash, 1·95; soda, 5·40; water, 2·68. Mean specific gravity, 2·9–3·1. Nephelinite is a form of basalt with no felspar or olivine.

Leucite-basalt (Leucite-Basanite) contains little or no felspar, but has leucite in place of it. Externally it resembles ordinary basalt. This rock occurs among the extinct volcanoes of the Eifel and of Central Italy, and forms the lavas of Vesuvius. Leucitite contains no felspar and no olivine.

Melilite-basalt.—In continuation of Zirkel's research, A. Stelzner has shown that in some basalts the part of felspar and nepheline is played by melilite.[204] In outer appearance the rocks possessing this composition, and to which the name of Melilite-basalt has been given, cannot be distinguished from ordinary basalt. Under the microscope, the ground-mass appears to be mainly composed of transparent sections of melilite, either disposed without order, or ranged in fluxion lines round the large olivine and augite crystals; but it also contains chromite (?), microlitic augite, brown mica, abundant magnetite, with perowskite, apatite, and probably nepheline. (Swabian Alb, Bohemia, Saxon Switzerland, etc.)

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[202] For some account of the use of the word melaphyre see Brongniart, "Classification et Caractères minéralogiques des Roches homogènes et hétérogènes," 1827, p. 106. Naumann, "Lehrbuch der Geognosie," i. p. 587. Zirkel, "Petrographie," ii. p. 39. Rosenbusch, "Mikroskop. Physiogr." ii. p. 484.

[203] "Basaltgesteine," 1870.

[204] Neues Jahrb. (Beilageband), 1883, p. 369–439.

Under the awkward name of "ultra-basic," the following group of rocks is included in which the proportion of silica sinks to a still smaller amount than in the basalts.

Limburgite (Magma-basalt)—a fine-grained to vitreous rock composed of augite, olivine, magnetite or titaniferous iron, and apatite. The base is generally glassy and the proportion of silica in the rock is only about 42 per cent. The typical locality is Limburg, near the Kaiserstuhl in Baden.

Peridotite Group.—The rocks here embraced, stand at the extreme end of the basic igneous rocks as the rhyolites and granites stand at the opposite end of the acid series. They contain no felspar, or at least an insignificant proportion of it, and consist of olivine, with augite, hornblende or mica, magnetic or titaniferous iron, chromite and other allied minerals of the spinel type. They contain—silica, 39–45; alumina, 0–6; ferrous oxide, 8–10; lime, 0–2; magnesia, 35–48; and have a mean specific gravity between 3·0 and 3·3. When quite fresh these rocks have a holocrystalline structure, but they are generally more or less altered, and in their extreme condition of alteration form rocks known as serpentines. They occur for the most part as intrusive masses belonging to the deeper-seated portions of volcanic eruptions. The following varieties may be noticed:

Pikrite[205] (Palaeopikrite, Pikrite-porphyry)—a rock rich in olivine, usually more or less serpentinized, with augite, magnetite, or ilmenite, brown biotite, hornblende, or apatite; occurs as an eruptive rock among Palæozoic formations; is closely related to the diabases into which by the addition of plagioclase it naturally passes. When hornblende predominates over pyroxene the rock has been called hornblende-pikrite.

Lherzolite[206]—so named from L'herz in the Ariège, is a holocrystalline rock composed of olivine, diallage, and a rhombic pyroxene, with a lesser proportion of a spinelloid sometimes brown (chromite, picotite), sometimes green (pleonast), and iron ores.

Dunite, named by F. von Hochstetter from the Dun Mountain, New Zealand, consists of a granitoid mixture of olivine with chromite or other spinelloid. Such a rock passes naturally by alteration into a serpentine.

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205 So named from πικρός, bitter, in allusion to the large proportion of bitter-earth (Magnesia)—a character shared by all the peridotites. Gümbel, "Die Palaeolithischen Eruptivgesteine des Fichtelgebirges"; Munich, 1874.

206 On the eruptive nature of Lherzolite, see A. Lacrois, Compt. rend. cxv. (1892), pp. 974 and 976.

Serpentine.[207]—Under this name are included rocks which, whatever may have been their original character and composition, now consist mainly or wholly of serpentine. As already stated, olivine readily passes into the condition of serpentine, while the other minerals may remain nearly unaffected, as is admirably seen in some pikrites. Most serpentine-rocks originally consisted principally of olivine (see Fig. 33). Diorite, gabbro, and other rocks, consisting largely of magnesian silicates, likewise pass into serpentine. If varieties due to different phases of alteration were judged worthy of separate designation, each member of the peridotites might of course have a conceivable or actual representative among the serpentines. But without attempt-

a b c

Fig. 33.—Stages in the alteration of Olivine. A, the nearly fresh crystal; B, the alteration half completed; C, the crystal wholly serpentinized.

ing this minuteness of classification, we may with advantage treat by itself, as deserving special notice, the massive form of the mineral serpentine from whatsoever rock it may have originated.

Massive serpentine is a compact or finely granular, faintly glimmering, or dull rock, easily cut or scratched, having a prevailing dirty-green color, sometimes variously streaked or flecked with brown, yellow, or red. It frequently contains other minerals besides serpentine. One of its commonest accompaniments is chrysotile or fibrous serpentine, which in veinings of a silky lustre often ramifies through the rock in all directions. Other common inclosures are

[207] See Tschermak, Sitz. Akad. Wien, lvi. July, 1867; it was this author who first showed the derivation of serpentine from original olivine rocks; Bonney, Q. J. Geol. Soc. xxxiii. p. 884, xxxiv. p. 769; Geol. Mag. (2) vi. p. 362; (3) i. p. 406; Michel-Lévy, Bull. Soc. Géol. France, vi. 3d ser. p. 156; Sterry Hunt, Trans. Roy. Soc. Canada, i. (1883); Dathe, Neues Jahrb. 1876, pp. 236, 337, where Garnet-serpentine and Bronzite-serpentine are described from the Saxon granulite region. J. S. Diller, Bull. U. S. Geol. Surv. No. 38 (1887); M. E. Wadsworth, "Lithological Studies" (1884), p. 118.

bronzite, enstatite, magnetite, and chrome-spinels, besides traces of the original olivine, pyroxene, amphibole, mica, or felspar in the rocks which have been altered into serpentine.

Serpentine occurs in two distinct forms; 1st, in beds or bands intercalated among schistose rocks, and associated especially with crystalline limestones; 2dly, in dikes, veins, or bosses traversing other rocks.

As to its mode of origin, there can be no doubt that in most cases it was originally an eruptive rock, as is clearly shown by its occurrence in dikes and irregular bosses. The frequent occurrence of recognizable olivine crystals, or of their still remaining contours, in the midst of the serpentine-matrix, affords good grounds for assigning an eruptive origin to many serpentines which have no distinctly eruptive external form (Fig. 34). The rock cannot, of course, have been ejected as the hydrous magnesian silicate serpentine; we must regard it as having been originally an eruptive olivine rock, or a highly hornblendic or micaceous diorite, or olivine-gabbro. But, on the other hand, the intercalation of beds of serpentine among schistose rocks, and particularly the frequent occurrence of serpentine in connection with more or less altered limestones (West of Ireland, Highlands of Scotland) suggests another mode of origin in these cases. Some writers have contended that such serpentines are products of the alteration of dolomite, the magnesia having been taken up by silica, leaving the carbonate of lime behind as beds of limestone. Others have supposed the original rocks, from which the serpentines were derived, to have been a deposit from oceanic water, as has been suggested by Sterry Hunt in the case of those associated with the crystalline schists.[208] Beds of serpentine intercalated with limestone might conceivably have been due to the elimination of magnesian silicates from sea-water by organic agency, like the glauconite now found filling the chambers of *foraminifera*, the cavities of corals, the canals in shells, sea-urchin spines and other organisms on the floor of the present

Fig. 34.—Microscopic Structure of Serpentine (20 Diameters).

208 "Chemical Essays," p. 123.

sea.[209] Among the limestone and crystalline schists of Banffshire (p. 316), serpentine occurs in thick lenticular beds which possess a schistose crumpled structure and agree in dip with the surrounding rocks. They may have been deposits of contemporaneous origin with the limestones and schists among which they occur, and in association with which they have undergone the characteristic schistose puckering and crumpling. Sometimes they suggest a source from the alteration of highly basic volcanic tuffs. In other cases they may have been erupted peridotites which have acquired a schistose character from the same process of mechanical deformation that has played so large a part in producing the foliation of the crystalline schists.

III. Schistose (Metamorphic)

In this section is comprised a series of rocks which present a remarkable system of divisional planes that are not original but have been superinduced upon them. At the one end stand rocks which are unmistakably of sedimentary origin, for their original bedding can often be distinctly seen, and they also contain organic remains similar to those found in ordinary unaltered sedimentary strata. At the other end come coarsely crystalline masses, which in many respects resemble granite, and the original character of which is not obvious. An apparently unbroken gradation can be traced between these extremes, and the whole series has been termed "metamorphic" from the changed form in which its members are believed now to appear. In the earlier stages the change has taken the form of cleavage as in ordinary slate. Even in slate, however, as already remarked (p. 236), a beginning may be detected in the development of crystalline particles, and the crystalline re-arrangement may be traced in constantly advancing

[209] According to Berthier, one of the glauconitic deposits in a Tertiary limestone is a true serpentine. See Sterry Hunt, "Chem. Essays," p. 303.

progression until the whole mass has become crystalline, and forms what is known as a schist.

The Crystalline Schists, properly so called, constitute a well-defined series of rocks. They are mainly composed of silicates. Their structure is crystalline, but is distinguished from that of the Massive or Eruptive rocks by its more or less closely parallel layers or folia, consisting of

Fig. 35.—Profile of a piece of Gneiss, showing the lenticular character of its folia, natural size. (B. N. Peach.)

materials which have assumed a crystalline character along these layers. The folia may be composed of only one mineral, but usually consist of two or more, which occur either in distinct, often alternate laminæ, or intermingled in the same layer. This structure resembles that of the stratified rocks, but it is differentiated (1) by a prevalent striking want of continuity in the folia, which, as a rule, are conspicuously lenticular, thickening out and then dying away, and reappearing after an interval on the same or a different plane (Fig. 35); (2) by a peculiar and very characteristic welding of the folia into each other, the crystalline particles of one layer being so intermingled with those of the layers above and below it that the whole coheres as a tough,

Fig. 36.—View of a hand-specimen of contorted mica-schist, two-thirds natural size. (B. N. Peach.)

not easily fissile mass; (3) by a frequent remarkable and eminently distinctive puckering or crumpling (with frequent minute faulting) of the folia, which becomes sometimes so fine as to be discernible only under the microscope[210] (Fig.

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[210] On the microscopic structure of the crystalline schists see Zirkel, "Microscopical Petrography" (vol. vi. of King's Exploration of 40th Parallel), 1876, p. 14. Allport, Q. J. Geol. Soc. xxxii. p. 407. Sorby, op. cit. xxxvi. p. 81, Lehmann's "Untersuchungen über d. Entstehung. Altkryst. Schiefer," Bonn, 1884; and other memoirs cited in subsequent pages.

37), but is often present conspicuously in hand-specimens (Fig. 36), and can be traced in increasing dimensions, till it connects itself with gigantic curvatures of the strata, which embrace whole mountains. These characters are sufficient to indicate a great difference between schistose rocks and ordinary stratified formations, in which the strata lie in continuous flat, parallel, and more or less easily separable layers.

In some instances, the folia can be seen to coincide with original bedding, as where a band of quartzite or of conglomerate is intercalated between sheets of phyllite or mica-schist. In such cases, there cannot be any doubt that the rock, though now more or less reconstructed and crystalline, was originally mere accumulated mechanical sediment. Many clay slates, phyllites, and mica-schists are obviously only altered marine clays, and some of them still retain their recognizable fossils. From such rocks, gradations can be followed into chiastolite-schist, mica-schist, and fine gneiss. Quartzites and quartz-schists often still retain the false-bedding of the original sandy sediment of which they are composed. The pebbly and conglomeratic bands associated with some schists afford convincing proof of their original clastic nature. Thus, at the one end of the schistose series we find rocks in which an original sedimentary character remains unmistakable. At the other end, after many intermediate stages, we encounter thoroughly amorphous crystalline masses, that bear the closest resemblance to eruptive rocks into which they insensibly pass. In such instances, there can be little doubt that the amorphous structure is the original one, which has become schistose by subsequent deformation (Book IV. Part. VIII.). The banded arrangement of many coarse gneisses, however, may be an original segregation-structure, like that observable in sills and bosses of eruptive rocks (p. 1035).

In the more thoroughly reconstructed and recrystallized schists all trace of the original structures has been lost. The foliation is not coincident with bedding, nor with any structure of eruptive rocks, but has been determined by planes of cleavage or of shearing, or by the alignment assumed by minerals crystallizing under the influence of intense pressure. Along these surfaces the constituents have rearranged themselves, and new chemical and mineralogical combinations have been effected during the progress of the "metamorphism."

A rock possessing a crystalline arrangement into separate folia is in English termed a Schist.[211] This word, though employed as a general designation to describe the structure of all truly foliated rocks, is also made use of as a suffix to the names of the minerals of which some of the foliated rocks largely consist. Thus we have "mica-schist," "chlorite-schist," "hornblende-schist." If the mass loses its fissile tendency, owing to the felting together of the component mineral into a tough coherent whole, the word rock is usually substituted for schist, as in "hornblende-rock," "actinolite-rock," and so on. The student must bear in mind that while the possession of a foliated structure is the distinctive character of the crystalline schists, it is not always present in every individual bed or mass associated with these rocks. Yet the non-schistose portions are so obviously integral parts of the schistose series that they cannot, without great violation of natural affinities, be separated

[211] In French this term has no such definite signification, being applied both to schists and to shales. In German also the corresponding word "schiefer" designates schists, but is also employed for non-crystalline shaly rocks; thonschiefer = clay-slate: schieferthon = shale.

from them. Hence in the following enumeration they are included as common accompaniments of the schists. Quartzite also may be placed in this subdivision, though in its typical condition it shows no schistose structure.

The origin of the crystalline schists has been the subject of long discussion among geologists. Werner held that, like other rocks of high antiquity, they were chemical precipitates from a universal ocean. Hutton and his followers maintained that they were mechanical aqueous sediments altered by subterranean heat. These two doctrines in various modifications are still maintained by opposite schools. In recent years much light has been thrown upon the origin of the schistose structure, which has been shown to be in many cases due to the mechanical crushing and chemical readjustment and recrystallization of the materials of both sedimentary and igneous rocks. This subject is discussed in a later part of this work. (See Book IV. Part VIII.)

It is obvious that a wide series of rocks embracing variously altered forms of both sedimentary and igneous materials hardly admits of any simple system of classification. Regarding them from the point of view of the nature of the metamorphism they have undergone, geologists have sometimes grouped these rocks as resulting either from contact metamorphism, that is, from the effects of the protrusion of igneous matter from within the earth's interior, or from regional metamorphism where the changes have been brought about by some widespread terrestrial disturbance (Book IV. Part VIII.). But this arrangement, though of value in discussing questions of metamorphism, has the disadvantage of introducing theoretical considerations, and of placing in different groups rocks which undoubtedly present the same general petrographical characters. Avoiding all disputed questions as to modes of origin, I shall group the schists according to their mineral characters, beginning with those which are obviously only a further stage of the alteration of clay-slates, and ending with the gneisses, which bear a close affinity to granites.

1. ARGILLITES, ARGILLACEOUS SCHISTS, PHYLLITES.—The rocks included in this group may often be traced into the clay-slates described on p. 235. They mark a further stage of metamorphism, wherein besides mechanical deformation there has been a more or less decided recrystallization of the materials, which is demonstrated by the abundant secondary mica and by the appearance of such minerals as chiastolite, andalusite, staurolite, garnet, etc. When a clay-slate becomes lustrous by the development of mica, it is known as Phyllite—a term which may be regarded as embracing the intermediate group of rocks between normal clay-slates and true mica-schists.

Chiastolite-slate (schiste maclé), a clay-slate in which crystals of chiastolite have been developed, even sometimes side by side with still distinctly preserved graptolites or other organic remains[212] (Skiddaw, Aberdeenshire, Brittany, the Pyrenees, Saxony, Norway, Massachusetts, etc.). Staurolite-slate, a micaceous clay-slate with crystals of staurolite (Banffshire, Pyrenees). Ottrelite-slate, a clay-slate marked by minute, six-sided, grayish or blackish green lamellæ of ottrelite (Ardennes, where it is said to contain remains of trilobites, Bavaria, New England). Dipyre-slate is full of small crystals of dipyre. Sericite-phyllite is a name proposed by Lossen for those compact, greenish, reddish, or violet sericite-schists in which the naked eye can no longer distinguish the component minerals. Mica-phyllite (*phyllade gris feuilleté* of Dumont), a silky, usually very fissile slate, with minute scales of mica. German petrographers have distinguished by name some other varieties found in metamorphic areas and characterized by different kinds of concretions, but to which no

[212] A good illustration of this association is figured by Kjerulf in his "Geologie des Südlichen und Mittleren Norwegen," Plate xiv. fig. 246. See also Brögger's memoir on Upper Silurian fossils among the crystalline rocks of Bergen. Christiania, 1882. A similar association occurs in the graptolite-shales next the granite of Galloway, Scotland.

special designations have been given in English. Knotenschiefer (Knotted schist) contains little knots or concretions of a dark-green or brown, fine-granular, faintly glimmering substance, of a talcose or micaceous nature, imbedded in a finely-laminated matrix of a talc-like or mica-like mineral.[213] These aggregations appear to be in many cases incipient stages in the formation of definite crystals of such minerals as andalusite. In Fruchtschiefer the concretions are like grains of corn; in Garbenschiefer, like caraway seeds; in Fleckschiefer, like flecks or spots. Some of these rocks might be included with the mica-schists, into varieties of which they seem to pass. Round some of the eruptive diabase of the Harz, the clay-slates have been altered into various crystalline masses to which names have been attached. Thus Spilosite is a greenish, schistose rock, composed of finely granular or compact felspathic material, with small chlorite concretions or scales. Desmosite is a schistose mass in which similar materials are disposed in more distinct alternations.[214]

2. QUARTZ ROCKS.[215]—**Quartz-schist** (schistose quartzite), an aggregate of granular (or granulitic) quartz with a sufficient development of fine folia of mica to impart a more or less definitely schistose structure to the rock. The disappearance of the mica gives quartzite, and the greater prominence of this mineral affords gradations into mica-schist. Such gradations are quite analogous to those among recent sedimentary materials from pure sand, through muddy sand, and sandy mud, into mud or clay, and between sandstones and shales. The Highlands of Scotland, for instance, embrace large tracts of quartz-schists-rocks which are not properly either mica-schist or ordinary quartzite. They consist of granular (granulitized) quartz, with fine parallel laminæ of mica, and are capable of being split into thick or thin flagstones. Interstratified pebbly varieties occur.

Itacolumite—a schistose quartzite, in which the quartz-granules are separated by fine scales of mica, talc,

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[213] A. von Lasaulx, Neues Jahrb. 1872, p. 840. K. A. Lossen, Z. Deutsch. Geol. Ges. 1867, p. 585 (where a detailed description of the Taunus phyllites will be found), 1872, p. 757.

[214] Other names are Bandschiefer, Contactschiefer, etc. See K. A. Lossen, Zeitsch. Deutsch. Geo. Ges. xix. (1867), p. 509, xxi. p. 291, xxiv. p. 701. Kayser, op. cit. xxii. p. 103.

[215] J. Macculloch, Trans. Geol. Soc. 1st ser. ii. (1814), p. 450, iv. (1817), p. 264; 2d ser. i. (1819), p. 53. Lossen, Zeitsch. Deutsch. Geol. Ges. xix. (1867), pp. 615–634.

chlorite, and sericite. Occasionally these pliable scales are so arranged as to give a certain flexibility to the stone (flexible sandstone). This rock occurs in the southeastern States of North America; also in Brazil, as the matrix in which diamonds are found.

Siliceous schist (Lydian stone, Lydite, Kieselschiefer) has already been described (p. 268) among the stratified rocks; but it also occurs among the crystalline schists, sometimes as the result of the pulverization of quartzose rocks (mylonite).

Quartzite (Quartz-rock), though not properly a schistose rock, may be most conveniently considered here, as it is so constant an accompaniment of the schists, and, like them, can often be directly traced to the alteration of former sedimentary formations. It is a granular to compact mass of quartz, generally white, sometimes yellow or red with a characteristic lustrous fracture. It occurs in thin and thick beds in association with schists, sometimes in continuous masses several thousand feet thick. In Scotland it forms

Fig. 37.—Contorted Micaceous-schist, as seen under the microscope with a magnifying power of 50 diameters.

Fig. 38.—Microscopic Structure of Quartzite. (Magnified 20 diameters.)

ranges of mountains, and is there frequently accompanied by beds of limestone, which in Sutherlandshire contain Cambrian fossils.[216]

Even to the naked eye, the finely granular or arenaceous structure of quartzite is distinctly visible. Microscopic examination shows this structure still more clearly, and leaves no doubt that the rock originally consisted of a tolerably pure quartz-sand (Fig. 38). More or less distinct evidence

[216] See the chapters on the Pre-Cambrian and Cambrian systems postea. On the metamorphic quartzose rocks of Morbihan, France, see Barrois, Ann. Soc. Géol. Nord, xi. (1884).

of crushing and deformation of the grains may often be observed, likewise proof of the transfusion of a siliceous cement among the particles. This cement was probably produced by the solvent action of heated water upon the quartz grains, which seem to shade off into each other, or into the intervening silica. It is owing, no doubt, to the purely siliceous character of the grains that the blending of these with the surrounding cement is so intimate as often to give the rock an almost flinty homogeneous texture. That quartzite, as here described, is an original sedimentary rock, and not a chemical deposit, is shown not only by its granular texture, but by the exact resemblance of all its leading features to ordinary sandstone—false-bedding, alternation of coarser and finer layers, worm-burrows, and fucoid-casts. The lustrous fracture that distinguishes this rock from sandstone is due to the exceedingly firm cohesion of the component grains, which break across rather than separate, and to the consequent production of innumerable minute clear vitreous surfaces of quartz. A sandstone, on the other hand, has its grains so loosely coherent that when the rock is broken the fracture passes between them, and the new surface obtained presents innumerable dull rounded grains.

Besides occurring in alternation with schists, quartzite is also met with locally as an altered form of sandstone, which, when traversed by igneous dikes, is indurated for a distance of a few inches or feet from the intrusive mass. These local productions of quartzite show the characteristic lustrous fracture, and have not yet been distinguished by the microscope from the quartz-rock of wide metamorphic regions. There is yet another condition under which this rock, or one of analogous structure, may be seen. Highly silicated bands, having a lustrous aspect, fine grain, and great hardness, occur among the unaltered shales and other strata of the Carboniferous system. In such cases the supposition of any general metamorphism being inadmissible, we may infer either that these quartzose bands have been indurated, for example, by the passage through them of thermal silicated water, or that they are an original formation.

Schistose Conglomerate Rocks.—In some regions of schists, not only bands of quartzite occur, representing former sandstones, but also pebbly or conglomeratic bands, in which pebbles of quartz and other materials from less than an inch to more than a foot in diameter are imbedded in a foliated matrix, which may be phyllite, mica-schist, gneiss, quartzite, etc.[217] Examples of this kind are found in the pass of the Tete Noire between Martigny and Chamouni, in the Saxon granulite region, in the Bergen region of Norway, in the northwest of France, in northwest Ireland, in the islands of Islay and Garvelloch, and in Perthshire and other parts of the central Highlands of Scotland. The pebbles are not to be distinguished from the water-worn blocks of ordinary conglomerates; but the original matrix which incloses them has been so altered as to acquire a micaceous foliated structure, and to wrap the pebbles round as with a kind of glaze. These facts, like those already referred to in the structure of quartzite and argillaceous and quartz-schist, are of considerable value in regard to the theory of the origin of some crystalline schists.

3. PYROXENE-ROCKS.—**Augite-schist**—a fine-grained schistose aggregate of pale or dark-green augite, with sometimes quartz, plagioclase, magnetite, or chlorite; found rarely among the crystalline schists. Among the schistose rocks of the Taunus, Lossen has described some interesting varieties under the name of Augite-schist (Augitschiefer). They are green, compact, sometimes soft and yielding to the finger-nail, usually distinctly schistose, and interbedded with the gneisses and schists. They are composed of a fine dull diabase-like ground-mass, through which are dispersed crystals of augite, 1 to 2 mm. in length, which in the typical varieties are the only components distinctly recognizable by the naked eye.[218] **Augite-rock**—a granular aggregate of augite (with tourmaline, sphene, scapolite, etc.), found in beds in the Laurentian limestone of Canada. Malacolite-rock is a pale granular to compact, or even fibrous aggregate of malacolite found in beds in crystalline limestone (Riesengebirge). **Schistose Gabbro**—a granular to schistose aggregate of plagioclase and diallage, occurs in lenticular bands among the amphibolites and granulites of the crystalline schists. The diallage may occur in conspicuous crystals, and is sometimes associated with abundant olivine, as in ordinary gabbro (p. 268).[219]

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[217] Prof. Wichmann describes some curious examples of serpentine conglomerates. See his paper in "Beiträge zur Geologie Ost-Asiens und Australiens," ii. pp. 35, 111. On the conglomerate-schists of Saxony, see A. Sauer, "Geol. Specialkarte Sachsen," Sect. "Elterlein," also Lehmann's "Altkryst. Schiefergesteine," p. 124. Reusch, "Silurfossiler og Pressede Konglomerater," Christiania, 1882. Barrois, Ann. Soc. Géol. Nord. xi. 1884.

[218] Lossen, Zeitsch. Deutsch. Geol. Ges. xix. (1867), p. 598.

[219] Rocks of this character occur in the Saxon "Granulitgebirge" and also

These pyroxenic intercalations among the schists, like the hornblendic and olivine bands mentioned below, seem to represent bands of igneous material (lavas or tuffs) either erupted contemporaneously with the deposition of the original material of the schists, or subsequently intruded into it, and thereafter exposed to the metamorphism which produced the foliation of the schists.

4. HORNBLENDE-ROCKS.—**Amphibolites**—a name applied to a group of rocks, composed mainly of hornblende, sometimes schistose, sometimes thick-bedded. Besides the hornblende, numerous other minerals, such as are common among the schists, likewise occur—orthoclase, plagioclase, quartz, augite and varieties, garnet, zoisite, mica, rutile, etc. Where the rock is schistose, it becomes an **amphibolite-schist** or **hornblende-schist**; or if the hornblende takes the form of actinolite, Actinolite-schist. Glaucophane-schist —a bluish-gray or black rock, in which the hornblende occurs in the form of glaucophane, forms large masses in the Southern Alps, and occurs locally in Anglesey. Where an amphibolite is not schistose, it used to be termed *hornblende-rock*. Nephrite (Jade) is a compact, extremely finely fibrous variety. The presence of other minerals in noticeable quantity may furnish names for other varieties. Thus, where plagioclase (and some orthoclase) occurs, the rock becomes a Felspar-amphibolite, Dioritic amphibolite, or Diorite-schist.[220] Amphibolites occur as bands associated with gneiss and other schistose formations. It was suggested by Jukes that they may possibly represent former beds of hornblendic or augitic lava and tuff, which have been metamorphosed together with the strata among which they were intercalated. This suggestion has received confirmation from the researches of the Geological Survey in the north of Scotland and in Ireland, where what were doubtless originally pyroxenic masses erupted prior to the metamorphism of the region, have had their augite changed by paramorphism into hornblende, and have partially assumed a foliated structure, passing into Epidiorite, Epidiorite-schist, amphibolite-schists, and even serpentine.

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in Lower Austria. F. Becke, Tschermak's Min. Mitth. IV. p. 352. J. Lehmann's "Untersuchungen über die Entstehung der Altkrystallinischen Schiefergesteine," Bonn, 1884, p. 190. On the diabase-schists of the Taunus, see L. Milch, Zeitsch. Deutsch. Geol. Ges. xli. (1889), p. 394.

[220] See F. Becke, Tschermak's Min. Mitth. IV. p. 233. The author likewise distinguishes diallage-amphibolite, garnet-amphibolite, salite-amphibolite, zoisite-amphibolite.

The connection of some schists with original masses of diorite, gabbro, and diabase has been pointed out by Lehmann and subsequently by many other observers.[221]

5. Garnet-Rocks.—**Eclogite**, one of the most beautiful members of the crystalline-schist series, is a granular aggregate of grass-green omphacite (pyroxene) and red garnet, through which are frequently dispersed bluish kyanite and white mica. It occurs in bands in the Archæan gneiss and mica-schist. To those varieties where the kyanite becomes predominant, the name of Kyanite-rock has been given. Garnet-rock is a crystalline-granular rock composed mainly of garnet, with hornblende and magnetite; by the diminution of the garnet it passes into an amphibolite. Kinzigite—a crystalline schistose rock, composed of plagioclase, garnet, and black mica, found in the Black Forest (Kinsig) and the Odenwald.

6. Epidote-Rocks.—**Epidosite** (Pistacite-rock)—an aggregate of bright green epidote with some quartz, occurs with chlorite-schist (Canada), with granite and serpentine (Elba), and with syenite. Epidote-schist, a schistose greenish rock, with silvery lustre on the foliation surfaces, composed of epidote, sericite, magnetite, quartz, calcite, plagioclase, and specular iron.[222]

7. Chlorite-Rocks.—**Chlorite-schist**—a scaly schistose aggregate of greenish chlorite, usually with quartz and often with felspar, talc, mica, or magnetite, the last-named mineral frequently appearing in beautifully perfect disseminated octohedra. Occurs with gneiss and other schists in evenly bedded masses.

8. Talc-Rocks.—**Talc-schist**—a schistose aggregate of scaly talc, often with quartz, felspar, and other minerals; having an unctuous feel, and white or greenish color. Occurs somewhat rarely in beds associated with mica-schist and clay-slate, and frequently contains magnetite, chlorite, mica, kyanite, and other minerals, including carbonates. A massive variety, composed of a finely felted aggregate of

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[221] "Untersuchungen über die Entstehung der Altkrystall Schief." See also Gümbel, "Die Paläolitischen Eruptivgesteine des Fichtelgebirges," Munich, 1874, p. 9; Teall, Quart. Journ. Geol. Soc. xli. (1883), p. 133; "British Petrography," p. 198. Hatch, Mem. Geol. Survey, Explanation of Sheets, 138, 139, Ireland, p. 49. Hyland, Mem. Geol. Survey, Explanations of Northwest Donegal, and of Southwest Donegal, Petrographical appendices, also postea, Book IV. pt. viii. G. H. Williams, Bull. U. S. Geol. Surv. No. 62, 1890.

[222] See Wichmann on Rocks of Timor, "Beiträge zur Geologie Ost-Asiens und Australiens," II. part 2, p. 97, Leyden, 1884.

scales of talc, with chlorite and serpentine, is called Potstone (Topfstein). Many rocks with a soapy or unctuous feel have been classed as talc-schist, which contain no talc, but a variety of mica (sericite-schist, etc.). Talc-schist, though not specially abundant, occurs in considerable mass in the Alps (Mont Blanc, Monte Rosa, Carinthia, etc.), and is found also among the Apennine and Ural mountains.

9. OLIVINE-ROCKS, or PERIDOTITES of the Crystalline Schists.[223] Rocks of which olivine forms a main constituent, occur as subordinate bands or irregular masses associated with gneisses and other schistose rocks. They were probably eruptive masses, contemporaneous with or subsequent to the surrounding gneisses and schists (p. 314). The olivine is commonly associated with some pyroxenic mineral, hornblende, garnet, etc. Some of the rocks mentioned on p. 300 may also be included here. Dunite, for example, which occurs in apparently eruptive form at Dun Mountain, near Nelson, New Zealand, is found in North Carolina in beds with laminated structure intercalated in hornblende-gneiss. Many of these rocks have undergone much crushing and deformation, and pass into foliated forms of Serpentine, which must thus be reckoned as one of the schistose as well as one of the eruptive series. Some remarkable schistose serpentines occur interbedded among phyllites, mica-schists, and limestones in Banffshire.

10. FELSITOID-ROCKS.—These are distinguished by an exceedingly compact felsite-like matrix. They occur in beds or bed-like masses, sometimes in districts of contact metamorphism, sometimes associated with vast masses of schists.

Halleflinta—an exceedingly compact, hornstone-like, felsitic, gray, yellowish, greenish, reddish, brownish, or black, rock, composed of an intimate mixture of microscopic particles of felspar and quartz, with fine scales of mica and chlorite. It breaks with a splintery or conchoidal fracture, presents under the microscope a finely-crystalline structure, occasionally with nests of quartz, and is only fusible in fine splinters before the blow-pipe. Some of the rocks to which this name has been applied are probably felsitic lavas; others, though externally presenting a resemblance to fel-

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223 See Tschermak, Sitzb. Akad. Wissen., Vienna, lvi. (1867). F. Becke, Tschermak's Min. Mitth. IV. (1882), p. 322. E. Dathe, Neues Jahrb. 1876, pp. 255–337.

site, occur in beds intimately associated with foliated rocks (Norway), and may be metamorphic products (perhaps altered fine sediments) due to the same series of changes that gave rise to the crystalline schists among which they lie.[224]

Adinole (Adinole-schist)—a rock externally resembling the last, but distinguished from it by its greater fusibility. It is an intimate mixture of quartz and albite, containing about ten per cent of soda. It is a product of alteration, being found among the altered Carboniferous shales around the eruptive diabases of the Harz, in the altered Devonian rocks of the Taunus, and in the altered Cambrian rocks of South Wales.[225]

Porphyroid—a name bestowed upon certain rocks composed of a felsite-like ground-mass which has assumed a more or less schistose structure from the development of micaceous scales, and which contains porphyritically scattered crystals of felspar and quartz. The felspar is either orthoclase or albite, and may be obtained in tolerably perfect crystals. The quartz occasionally presents doubly terminated pyramids. The micaceous mineral may be paragonite or sericite. Porphyroid occurs in circumstances which suggest considerable mechanical deformation, as among the schistose rocks of Saxony,[226] in the Palæozoic area of the Ardennes,[227] as well as in Westphalia and other parts of Europe.[228] Some porphyroids are probably sheared forms of quartz-porphyry, felsite, or some similar rock; others may be more of the nature of tuffs.

11. Quartz- and Tourmaline-Rocks.—**Tourmaline-schist** (Schorl-schist, schorl-rock), a blackish, finely granular, quartzose rock with abundant granules and needles of black tourmaline (schorl), which occurs as one of the products of contact-metamorphism in the neighborhood of some granites (Cornwall).

12. Quartz- and Mica-Rocks.—**Mica-schist** (Mica-slate, Glimmerschiefer), a schistose aggregate of quartz and mica,

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224 For analyses see H. Santesson, "Kemiska Bergsartanalyser," 8vo, Stockholm, 1877.

225 Lossen, Zeitsch. Deutsch. Geol. Gesel. xix. (1867), p. 573. See also Quart. Journ. Geol. Soc. xxxix. (1883), pp. 302, 320. Rosenbusch, "Mikroskopische Physiographie," ii. p. 235. F. Posepny, Tschermak's Mineral. Mitth. x. 175.

226 Rothpletz, Geol. Survey Saxony, Explanation of Section Rochlitz.

227 De la Vallée Poussin and Renard, Mem. Couronnées Acad. Roy. Belg. 1876, p. 85.

228 Lossen, Sitz. Gesellsch. Naturf. Freunde, 1883, No. 9.

the relative proportions of the two minerals varying widely even in the same mass of rock. Each is arranged in lenticular wavy laminæ. The quartz shows great inconstancy in the number and thickness of its folia. It often presents a granular character, like that of quartz-rock, or passing into granulite. The mica lies in thin plates, sometimes so dovetailed into each other as to form long continuous irregular crumpled folia, separating the quartz layers, and often in the form of thin spangles and membranes running in the quartz. (Figs. 36 and 37.) As the rock splits open along its micaceous folia, the quartz is not readily seen save in a cross fracture.

The mica in typical mica-schist is generally a white variety; but it is sometimes replaced by a dark species. In many lustrous, unctuous schists which are now found to have a wide extent, the silvery foliated mineral is ascertained to be a mica (margarodite, damourite, etc.), and not talc, as was once supposed. These were named by Dana hydro-mica-schists. Among the accessory minerals, garnet (specially characteristic), schorl, felspar, hornblende, kyanite, staurolite, chlorite, and talc may be mentioned. Mica-schist readily passes into other members of the schistose family. By addition of felspar, it merges into gneiss. By loss of quartz and increase of chlorite, it passes into chlorite-schist, and by loss of mica, into quartz-schist and quartzite. By failure of quartz and diminution of mica, with an increasing admixture of calcite, it may shade into calc-mica-schist (see below), and even into marble. Mica-schist varies in color mainly according to the hue of its mica.

Mr. Sorby has stated that thin slices of some mica-schists, when examined under the microscope, show traces of original grains of quartz-sand and other sedimentary particles of which the rock at first consisted. He has also found indications of what he supposes to have been current-bedding or ripple-drift, like that seen in many fine sedimentary deposits, and he concludes that mica-schist is a crystalline metamorphosed sedimentary rock.[229] In many, if not in most cases, however, the foliation does not correspond with original bedding, but with structural planes (cleavage, faulting) superinduced by pressure, tension, or

[229] Q. J. Geol. Soc. (1863), p. 401, and his address in vol. xxxvi. (1880), p. 85. The apparent current-bedding of many granulitic and other metamorphic rocks is certainly deceptive, and must be due to planes of shearing or slipping in the mechanical movements which produced the metamorphism.

otherwise, upon rocks which may not always have been of sedimentary origin.

Among the varieties of mica-schist may be mentioned Sericite-schist (which may be also included among the phyllites), composed of an aggregate of fine folia of the silky variety of mica called sericite, in a compact honestone-like quartz; Paragonite-schist, where the mica is the hydrous soda variety, paragonite; Gneiss-mica-schist, containing dispersed kernels of orthoclase. Some of these rocks contain little or no quartz, the place of which is taken by felspar. Calc-mica-schist, a schistose calcareous rock, which in many, if not in all cases, was originally a limestone with more or less muddy impurity. The carbonate of lime has assumed a granular-crystalline form, while the aluminous silicates have recrystallized as fine scales of white mica. Tremolite, zoisite, and other minerals are not infrequent in this rock.

Normal mica-schist, together with other schistose rocks, forms extensive regions in Norway, Scotland, the Alps, and other parts of Europe, and vast tracts of the "Archæan" regions of North America. Some of its varieties are also found encircling granite masses (Scotland, Ireland, etc.) as a zone or aureole of contact-metamorphism from a few yards to a mile or so broad, which shades away into unaltered graywacke or slate outside. In these cases, mica-schist is unquestionably a metamorphosed condition of ordinary sedimentary strata, the change being connected with the extravasation of granite. (Book IV. Part VIII.)

Though the possession of a fissile structure, showing abundant divisional surfaces covered with glistening mica, is characteristic of mica-schist, we must distinguish between this structure and that of many micaceous sandstones which can be split into thin seams, each splendent with the sheen of its mica-flakes. A little examination will show that in the latter case the mica has not crystallized *in situ*, but exists merely in the form of detached worn scales, which, though lying on the same general plane, are not welded into each other as in a schist; also that the quartz does not exist in folia but in rounded separate grains.

13. Quartz- and Felspar-Rocks.—The replacement of the mica of a mica-schist by felspar, or the disappearance of the mica from a gneiss, gives rise to an aggregate of felspar and quartz. Such a rock may be observed in thin bands or courses, alternating with the surrounding mass. In mineral composition, it may be compared to the quartz-

porphyries or granite-porphyries of the massive rocks, but it is usually distinguishable by a more or less foliated structure, and by the absence of felsitic ground-mass.

14. QUARTZ-, FELSPAR-, AND MICA-ROCKS.—**Gneiss.**—This name, formerly restricted to a schistose aggregate of orthoclase (sometimes microline or a plagioclastic felspar, either separate or crystallized together), quartz, and mica, is now commonly employed in a wider sense to denote the coarser schists which so often present granitoid characters.[230] Many gneisses, indeed, differ from granite chiefly in the foliated arrangement of the minerals. The quartz sometimes contains abundant liquid inclusions, in which liquid carbon-dioxide has been detected. The relative proportions of the minerals, and the manner in which they are grouped with each other, present great variations. As a rule, the folia are coarser, and the schistose character less perfect than in mica-schist. Sometimes the quartz lies in tolerably pure bands, a foot or even more in thickness, with plates of mica scattered through it. These quartz layers may be replaced by a crystalline mixture of quartz and felspar, or the felspar will take the form of independent lenticular folia, while the laminæ of mica which lie so abundantly in the rock give it its fissile structure. The felspar of many gneisses presents under the microscope a remarkable fibrous structure, due to the crystallization of fine lamellæ of some plagioclase (albite or oligoclase) in the main mass of orthoclase or microcline.[231] Among the accessory minerals, garnet, tourmaline or schorl, hornblende, apatite, graphite, pyrites, and magnetite may be enumerated.

There can be no doubt that many gneisses owe their characteristic schistose structure to the crushing and shearing of some original eruptive rock such as granite. Instances, however, occur where the materials are segregated in bands which so closely resemble those of true flow-structure or segregation in igneous bosses and sheets as to suggest that they may possibly have resulted from the movement of a still unconsolidated eruptive mass (pp. 306, 1022). Analogies to such structures may be observed among ancient and modern lavas.

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[230] See Kalkowsky's "Gneissformation des Eulengebirges," Leipzig, 1878; Lehmann's "Altkrystallinische Schiefergesteine," 1884; F. Becke, Tschermak's Min. Mitth. 1882, p. 194; E. Weber, op. cit. 1884, p. 1, and postea Book IV. Part VIII. § ii. and Book VI. Pre-Cambrian.

[231] F. Becke (Tschermak's Min. Mitth. 1882, (iv.) p. 198) described this structure and named it *microperthite*.

Many varieties of gneiss occur. Some are distinguished by peculiarities of structure or composition, as Granite-gneiss, where the schistose arrangement is so coarse as to be unrecognizable, save in a large mass of the rock; Diorite-gneiss, gabbro-gneiss, composed of the materials of a diorite or gabbro but with a coarsely schistose structure; Porphyritic gneiss or Augen-gneiss, in which large eye-like kernels of orthoclase or quartz are dispersed through a finer matrix and represent larger crystals or crystalline aggregates which have been broken down and dragged along by shearing movements in the rock. Other varieties are named from the occurrence in them of one or more distinguishing minerals, as Hornblende-gneiss (syenitic gneiss), in which hornblende occurs instead of or in addition to mica; Protogine-gneiss, where the ordinary mica is altered into chlorite or a talc-like substance; Sericite-gneiss, a schistose aggregate of sericite, albite, quartz, with less frequently white and black mica and a chloritic mineral;[232] Augite-gneiss, containing an augitic mineral (not of the diallage group) and potash-felspar or potash-soda-felspar or scapolite, with hornblende (which has often crystallized parallel with the augite), brown mica, more or less quartz, and also frequently with garnet, calcite, titanite, etc.;[233] Plagioclase-gneiss, with plagioclase more abundant than orthoclase, sometimes containing hornblende, sometimes augite; Cordierite-gneiss, with the bluish vitreous mineral cordierite.

The most typical gneisses occur among the so-called "Archæan rocks," of which they form the leading type, and where they probably represent original eruptive rocks. (See Book VI. Part I.) They cover considerable areas in Scandinavia, N. W. Scotland, Bohemia, Bavaria, Erzgebirge, Moravia, Central Alps, Canada, etc. But rocks to which the name of gneiss cannot be refused appear also among the products of the metamorphism of various stratified formations. Such are the gneisses associated with many other crystalline schists among the altered Cambrian and Silurian rocks of Scotland, Norway, and New England,

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[232] K. A. Lossen, Zeitsch. Deutsch. Geol. Ges. xix. (1867), p. 565.

[233] The occurrence of augite as an abundant constituent of some gneisses has been made known by microscopic research. Rocks of this nature occur in Sweden (A. Stelzner, N. Jahrb. 1880 (ii.), p. 103), and have been fully described from Lower Austria (F. Becke, Tschermak's Min. Mitth. 1882 (iv.), pp. 219–365). They are likewise well developed among the oldest gneisses of the northwest of Sutherland in Scotland.

the altered Devonian rocks of the Taunus, and other regions, which will be described in Book IV. Part VIII. Some of these may also be eruptive granites, diorites, etc., which have undergone shearing and have acquired a schistose character.

15. QUARTZ-, FELSPAR-, AND GARNET-ROCKS.—**Granulite**[234] (Eurite-schistoïde, Leptynite of French authors, Weiss-stein) —a fine-grained granular aggregate of pale reddish, yellowish, or white felspar with quartz and small red garnets, occasionally with kyanite, biotite, and microscopic rutile and tourmaline. The felspar, which is the predominant constituent, presents the peculiar fibrous structure referred to in the foregoing description of gneiss (microperthite, microcline), and appears seldom to be true orthoclase. The quartz is conspicuous in thin partings between thicker more felspathic bands, giving a distinctly fissile bedded character to the mass. A dark variety, interstratified with the normal rock, is distinguished by the presence of microscopic augite or diallage (Augitgranulite of Saxony). Granulite occurs in bands among the gneiss and other members of the crystalline schist series in Saxony, Bohemia, Lower Austria, the Vosges, and Central France. The term "granulite" is also employed in a structural sense to denote a rock which has been crushed down by dynamic metamorphism, and has acquired this characteristic fine granular structure. (See pp. 177, 211.)

16. FELSPAR- AND MICA-ROCKS.—Rocks composed essentially of a schistose aggregate of minutely scaly mica with some felspar, quartz, andalusite, or other mineral, occur in regions of metamorphism. C o r n u b i a n i t e was a name proposed by Boase for a rock composed of a felspar base, with abundant mica.[235] It is found around the granite of Cornwall, of which it is a metamorphic product. By some writers this rock has been associated with the gneisses, but it is distinguished by the scarcity or absence of quartz.

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[234] Michel-Lévy has proposed to reserve the names "Leptynite" for schistose and "Granulite" for eruptive rocks. Bull. Soc. Géol. France, 3d ser. ii. pp. 177, 189, iii. p. 287, iv. p. 730, vii. p. 760; Lory, op. cit. viii. p. 14. Scheerer, Neues Jahrb. 1873, p. 673. Dathe, N. Jahrb. 1876, p. 225; Z. Deutsch. Geol. Ges. 1877, p. 274. Details regarding the great development of the granulite of Saxony (Granulitgebirge) will be found in the explanatory pamphlets published with the sheets of the Geological Survey of Saxony, especially those of sections Rochlitz, Geringswalde and Waldheim. The history of the origin of granulite is discussed by J. Lehmann, "Untersuchungen über die Entstehung der Altkrystall. Schiefergesteine."

[235] "Geology of Cornwall" (1832), pp. 226, 230.

COMPOSITION OF SOME SCHISTOSE ROCKS

	Spec. Grav.	Silica	Alumina	Iron, perox.	Iron, protox	Man-gan. protox	Lime	Magnesia	Potash	Soda	Water
Clay slate . . .	2·6—2·9	54—64	13—23	0—19	0—8·5	...	0·5—9	1—9·5	1—6	0·1—3·9	0—3·9
" alum slate . .	2·42	52·28	16·64	Fe S_2 7·74	9·96	...	1·53	1·10	7·98	(carbon) 4·37	1·40 loss
Talc-schist . . .	...	50—58	4·5—9·0	3·5—7·0	1·0	...	1·0—1·5	23·0—31·5	...	...	0—6
Chlorite-schist . .	2·7—2·9	42—55	3—14	0—4·5	9—27	0·5	0.2—1·5	8—17	0·6	0·2—1·5	4·5—11·2
Hornblende-schist .	3·0—3·1	48—50	13·3—16 4	12—27·5	4·5—9	0—0·5	0·6—12	2—2·6	0·5—1·2	1·9—2·3	...
Hornblende-rock .	2·94	49·42	18·12	5·41	9·60	...	8·65	3·16	1·27	2·57	1·80 loss
Mica-schist . . .	2·77	65·13	18·16	...	5·27	0·51	0·32	2·70	2·99	0·53	Ti O_2 1·54
Mica-gneiss . . .	2·70	65—75	13—21	0—5·8	0—6	0—0·8	1—5	0·5—3·0	1·5—4·8	0·5—2·5	...
Hornblende-gneiss .	2·80	56·83	19·68	2·88	5·76	trace	1·89	3·28	3·14	2·34	{ Ti O_2 0·47 { Cu O 0·09
Granulite (Leptynite)	2·66	73·47	14·86	...	3·28	....	1·62	0·67	3·95	1.80	H_2 O, 0·57

BOOK III

DYNAMICAL GEOLOGY

DYNAMICAL GEOLOGY investigates the processes of change at present in progress upon the earth, whereby modifications are made on the structure and composition of the crust, on the relations between the interior and the surface, as shown by volcanoes, earthquakes, and other terrestrial disturbances, on the distribution of land and sea, on the outlines of the land, on the form and depth of the sea-bottom, on marine currents, and on climate. Bringing before us, in short, the whole range of geological activities, it leads us to precise notions regarding their relations to each other, and the results which they achieve. A knowledge of this branch of the subject is thus the essential groundwork of a true and fruitful acquaintance with the principles of geology. The study of the present order of nature provides a key for the interpretation of the past.

The operations considered by Dynamical Geology may be regarded as a vast cycle of change, into the investigation of which the student may break at any point, and round which he may travel, only to find himself brought back to his starting-point. It is a matter of comparatively small moment at what part of the cycle the inquiry is begun. The changes seen in action will always be found to have resulted from some that preceded, and to give place to others that follow them.

At an early time in the earth's history, anterior to any of the periods of which a record remains in the visible rocks, the chief sources of geological energy probably lay within the earth itself. The planet still retained much of its initial heat, and in all likelihood was the theatre of great chemical changes. As it cooled, and as the superficial disturbances due to internal heat and chemical action became less marked, the influence of the sun, which must always have operated, and which in early geological times may have been more effective than it afterward became, would then stand out more clearly, giving rise to that wide circle of surface changes wherein variations of temperature and the circulation of air and water over the surface of the earth come into play.

In the pursuit of his inquiries into the past history and into the present economy of the earth, the student must needs keep his mind ever open to the reception of evidence for kinds, and especially for degrees, of action which he had not before encountered. Human experience has been too short to allow him to assume that all the causes and modes of geological change have been definitely ascertained. Besides the fact that both terrestrial and solar energy were once probably more intense than now, there may remain for future discovery evidence of former operations by heat, magnetism, chemical change, or other agency, that may explain phenomena with which geology has to deal. Of the influences, so many and profound, which the sun exerts upon our planet, we can as yet only perceive a little. Nor can we tell what other cosmical influences may have lent their aid in the revolutions of geology.

In the present state of knowledge, all the geological energy upon and within the earth must ultimately be traced back to the primeval energy of the parent nebula, or sun. There is, however, a certain propriety and convenience in distinguishing between that part of it which is due to the survival of some of the original energy of the planet, and that part which arises from the present supply of energy received day by day from the sun. In the former case, the geologist has to deal with the interior of the earth and its reaction upon the surface; in the latter, he is called upon to study the surface of the earth, and to some extent its reaction on the interior. This distinction allows of a broad treatment of the subject under two divisions:

I. Hypogene or Plutonic Action—the changes within the earth, caused by original internal heat and by chemical action.

II. Epigene or Surface Action—the changes produced on the superficial parts of the earth, chiefly by the circulation of air and water set in motion by the sun's heat.

Part I. Hypogene Action

An Inquiry into the Geological Changes in Progress beneath the Surface of the Earth

In the discussion of this branch of the subject, it is useful to carry in the mind the conception of a globe still intensely hot within, radiating heat into space, and consequently contracting in bulk. Portions of molten rocks from inside are from time to time poured out at the surface. Sudden shocks are generated, by which earthquakes are propagated to and along the surface. Wide geographical areas are upraised or depressed. In the midst of these movements, the rocks of the crust are fractured, squeezed, sheared, crumpled, rendered crystalline, and even fused.

Section i. Volcanoes and Volcanic Action[1]

§ 1. Volcanic Products

The term volcanic action (volcanism or volcanicity) embraces all the phenomena connected with the expulsion of heated materials from the interior of the earth to the surface. Among these phenomena, some possess an evanescent character, while others leave permanent proofs of their existence. It is naturally to the latter that the geologist gives chief attention, for it is by their means that he can trace former phases of volcanic activity in regions where, for many ages, there have been no volcanic eruptions. In the operations of existing volcanoes, he can observe only superficial manifestations of volcanic action. But examining the rocks of the earth's crust, he discovers that amid the many terrestrial revolutions which geology reveals, the very roots of former volcanoes have been laid bare, displaying subterranean

[1] The student is referred to the following general works on the phenomena of volcanoes. Scrope, "Considerations on Volcanoes," London, 1825; "Volcanoes," London, 2d edit. 1872; "Extinct Volcanoes of Central France," London, 1858; "On Volcanic Cones and Craters," Quart. Journ. Geol. Soc. 1859. Daubeny, "A Description of Active and Extinct Volcanoes," 2d edit., London, 1858. Darwin, "Geological Observations on Volcanic Islands," 2d edit., London, 1876. A. von. Humboldt, "Ueber den Bau und die Wirkung der Vulkane," Berlin, 1824. L. von Buch, "Ueber die Natur der vulkanischen Erscheinungen auf den Canarischen Inseln," Poggend. Annalen (1827), ix. x.; "Ueber Erhebungskratere und Vulkane," Poggend. Annalen (1836), xxxvii. E. A. von Hoff, "Geschichte der durch Ueberlieferung nachgewiesenen natürlichen Veränderungen der Erdoberfläche" (part ii., "Vulkane und Erdbeben"), Gotha, 1824. C. W. C. Fuchs, "Die vulkanischen Erscheinungen der Erde," Leipzig, 1865. R. Mallet, "On Volcanic Energy," Phil. Trans. 1873. J. Schmidt, "Vulkanstudien," Leipzig, 1874. Sartorius von Waltershausen and A. von Lasaulx, "Der Aetna," 4to, Leipzig, 1880. E. Reyer, "Beitrag zur Physik der Eruptionen," Vienna, 1877; "Die Euganeen; Bau und Geschichte eines Vulkanes," Vienna, 1877. Fouqué, "Santorin et ses éruptions," Paris, 1879. Judd, "Volcanoes," 1881. G. Mercalli, "Vulcani e Fenomeni vulcanici in Italia," Milan, 1883. Ch. Vélain, "Les Volcans," Paris, 1884. J. D. Dana, "Characteristics of Volcanoes," 1890. "Volcanoes Past and Present," E. Hull, 1892. "The South Italian Volcanoes," H. J. Johnston-Lavis, Naples, 1891. References will be found in succeeding pages to other and more special memoirs.

phases of volcanism which could not be studied in any modern volcano. Hence an acquaintance only with active volcanoes will not afford a complete knowledge of volcanic action. It must be supplemented and enlarged by an investigation of the traces of ancient volcanoes preserved in the crust of the earth. (Book IV. Part VII.)

The word "volcano" is applied to a conical hill or mountain (composed mainly or wholly of erupted materials), from the summit and often also from the sides of which, hot vapors issue, and ashes and streams of molten rock are intermittently expelled. The term "volcanic" designates all the phenomena essentially connected with one of these channels of communication between the surface and the heated interior of the globe. Yet there is good reason to believe that the active volcanoes of the present day do not afford by any means a complete type of volcanic action. The first effort in the formation of a new volcano is to establish a fissure in the earth's crust. A volcano is only one vent or group of vents established along the line of such a fissure. But in many parts of the earth, alike in the Old World and the New, there have been periods in the earth's history when the crust was rent into innumerable fissures over areas thousands of square miles in extent, and when the molten rock, instead of issuing, as it does at a modern volcano, in narrow streams from a central elevated cone, welled out from numerous small vents along the rents, and flooded enormous tracts of country without forming any mountain or conspicuous volcanic cone in the usual sense of these terms. Of these "fissure-eruptions," apart from central volcanic cones, no examples appear to have occurred within the times of human history, except in Iceland, where vast lava-floods issued from a fissure in 1783 (pp. 378, 434). They can best be studied from the remains of former convulsions. Their importance, however, has not yet been generally recognized in Europe, though acknowledged in America, where they have been largely developed. Much still remains to be done before their mechanism is as well understood as that of the lesser type to which all present volcanic action belongs. In the succeeding narrative an account is first presented of the ordinary and familiar volcano and its products; and in § 3, ii., some details are given of the general aspect and character of fissure-eruptions.

The openings by which heated materials from the interior now reach the surface include volcanoes (with their various associated orifices) and hot-springs.

The prevailing conical form of a volcano is that which the ejected materials naturally assume round the vent of eruption. The summit of the cone is truncated (Figs. 39, 45), and presents a cup-shaped or caldron-like cavity, termed the crater, at the bottom of which is the top of the main funnel or pipe of communication with the heated interior. A volcano, when of small size, may consist merely of one cone; when of the largest dimensions, it forms a huge mountain, with many subsidiary cones and many lateral fissures or pipes, from which the heated volcanic products are given out. Mount Etna (Fig. 39), rising from the sea to a height of 10,840 feet, and supporting, as it does, some 200 minor cones, many of which are in themselves considerable hills, is a magnificent example of a colossal volcano.[2]

[2] The structure and history of Etna are fully described in the great work of Sartorius von Waltershausen and A. von Lasaulx cited on p. 327—a treasure-house of facts in volcanic geology. See also G. F. Rodwell, "Etna, a history of the mountain and its eruptions," London, 1878; O. Silvestri, "Un Viaggio all' Etna," 1879. Notices of recent eruptions of the mountain will be found in Nature, vols. xix., xx., xxi., xxii., xxv. (observatory on Etna, p. 394), xxvii., xlvi.; Compt. rend. lxvi. The work of Mercalli, cited on p. 327, gives descriptions of this and the other Italian volcanic centres.

The materials erupted from volcanic vents may be classed as (1) gases and vapors, (2) water, (3) lava, (4) fragmentary substances. A brief summary under each of these heads

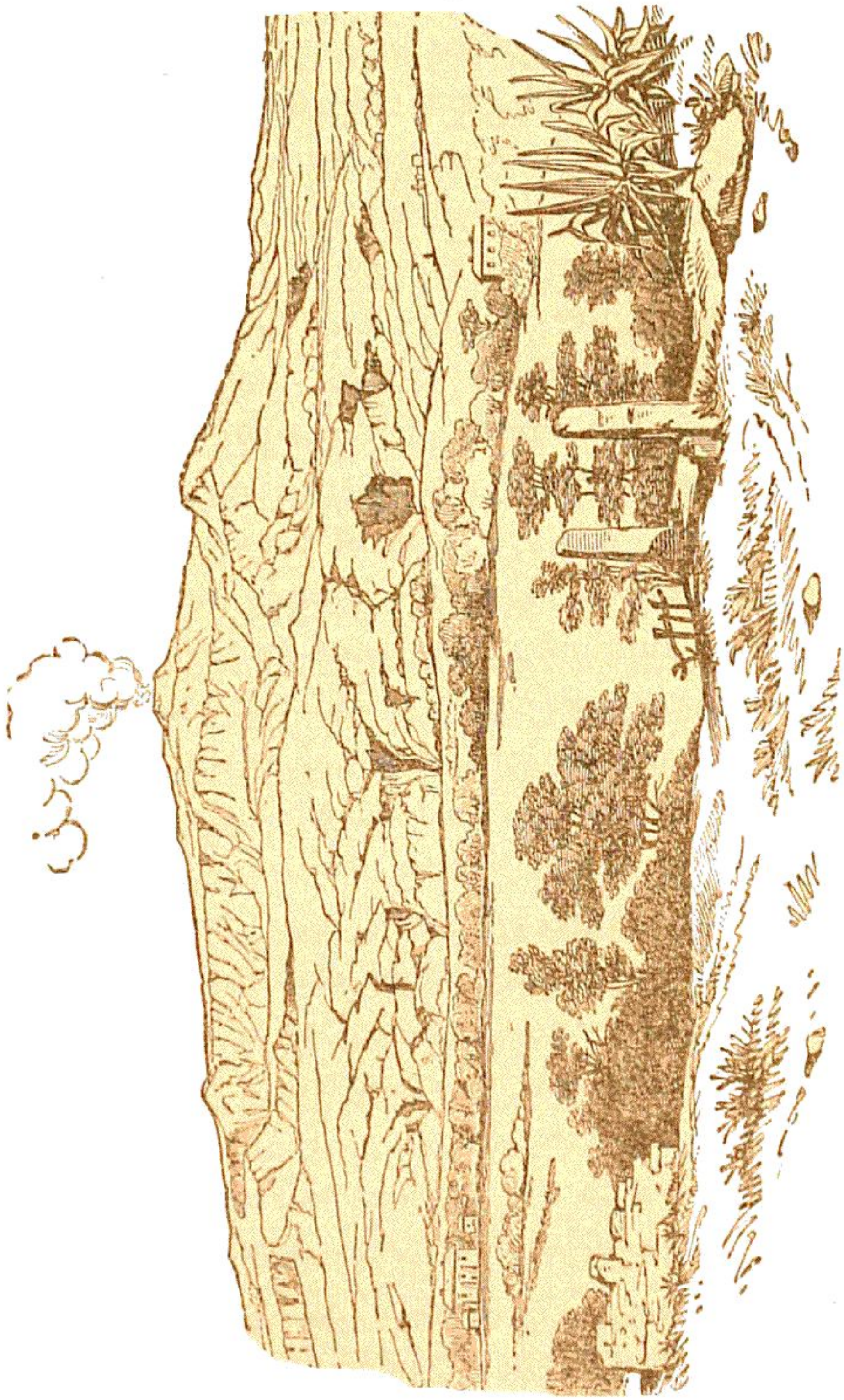

Fig. 39.—View of Etna from the Torre Archirafi (Sartorius von Waltershausen).

may be given here; the share taken by the several products in the phenomena of an active volcano is described in § 2.

1. **Gases and Vapors** exist dissolved in the molten magma

within the earth's crust. They play an important part in volcanic activity, showing themselves in the earliest stages of a volcano's history, and continuing to appear for centuries after all other subterranean action has ceased. By much the most abundant of them all is water-gas, which, ultimately escaping as steam, has been estimated to form $\frac{999}{1000}$ths of the whole cloud that hangs over an active volcano (Fig. 40). In great eruptions, steam rises in prodigious

Fig. 40.—View of Vesuvius as seen from Naples during the eruption of 1872, showing the dense clouds of condensed aqueous vapor.

quantities, and is rapidly condensed into a heavy rainfall. M. Fouqué calculated that, during 100 days, one of the parasitic cones on Etna had ejected vapor enough to form, if condensed, 2,100,000 cubic mètres (462,000,000 gallons) of water. But even from volcanoes which, like the Solfatara of Naples, have been dormant for centuries, steam sometimes still rises without intermission and in considerable volume. Jets of vapor rush out from clefts in the sides and bottom of a crater with a noise like that made by the steam blown off by a locomotive. The number of these funnels or "fumaroles" is often so large, and the amount of vapor so abundant, that only now and then, when the wind blows the dense cloud aside, can a momentary glimpse be had of a part of the bottom of the crater; while at the same time the rush and roar of the escaping steam remind one of the din of some vast factory. Aqueous vapor rises likewise from rents on the outside of the volcanic cone. It issues so copiously from some flowing lavas that the stream of rock may be almost concealed from view by the cloud; and it continues to escape from fissures of the lava, far below the point of exit, for a long time after the rock has solidified and come to rest. So saturated are many molten lavas with water-vapor that Mr. Scrope thought that they owed their mobility to this cause.[3] In the deep volcanic magma the water-substance must be far above its critical temperature, which is about 773° Fahr.

Probably in no case is the steam mere pure vapor of water, though when it condenses into copious rain, it is fresh and not salt water. It is associated with other vapors and gases disengaged from the potent chemical laboratory underneath. There seems to be always a definite order in the appearance of these vapors, though it may vary for different volcanoes. The hottest and most active "fumaroles," or vapor-vents, may contain all the gases and vapors of a volcano, but as the heat diminishes, the series of gaseous emanations is reduced. Thus in the Vesuvian eruption of 1855–56, the lava, as it cooled and hardened, gave out successively vapors of hydrochloric acid, chlorides, and

[3] "Considerations on Volcanoes" (1825), p. 110.

sulphurous acid; then steam; and, finally, carbon-dioxide and combustible gases.[4] More recent observations tend to corroborate the deductions of C. Sainte-Claire Deville that the nature of the vapors evolved depends on the temperature or degree of activity of the volcanic orifice, chlorine (and fluorine) emanations indicating the most energetic phase of eruptivity, sulphurous gases a diminishing condition, and carbonic acid (with hydrocarbons) the dying out of the activity.[5] A "solfatara," or vent emitting only gaseous discharges, is believed to pass through these successive stages. Wolf observed that on Cotopaxi while hydrochloric acid and even free chlorine escaped from the summit of the cone, sulphuretted hydrogen and sulphurous acid issued from the middle and lower slopes.[6] Fouqué's studies at Santorin have shown also that from submarine vents a similar order of appearance obtains among the volcanic vapors, hydrochloric and sulphurous acids being only found at points of emission having a temperature above 100° C.,

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[4] C. Sainte-Claire Deville and Leblanc, Ann. Chim. et Phys., 1858, lii. p. 19 *et seq.* For accounts of Vesuvius and its eruptions, besides the general works already cited on p. 327, consult J. Phillips' "Vesuvius," 1869; "Mount Vesuvius," J. L. Lobley, 1889; J. Schmidt, "Die Eruption des Vesuv. 1855," Vienna, 1856; Mercalli's "Vulcani, etc."; H. J. Johnston-Lavis, Q. J. Geol. Soc. xl. 35; Geol. Mag. 1888, p. 445. A diary of the volcano's behavior for six months is given in Nature, xxvi.; one for four years (1882–86) by Dr. Johnston-Lavis "Spettatore del Vesuvio," Naples, 1887; a valuable series of reports on the mountain by the same author will be found in recent volumes of the Reports of the British Association (1885–91) and a large detailed map of the volcano, also by him, published by Philip, London, 1891.

[5] He distinguished volcanic emanations according to their order of appearance as regards time, nearness to the vent, and temperature: viz. 1. Dry fumaroles (without steam), where anhydrous chlorides are almost the only discharge, and where the temperature is very high (above that of melted zinc). 2. Acid fumaroles, with sulphurous and hydrochloric acids and steam. 3. Alkaline (ammoniacal) fumaroles; temperature about 100° C.; abundant steam with chloride of ammonium. 4. Cold fumaroles; temperature below 100° C., with nearly pure steam accompanied by a little carbon-dioxide, and sometimes sulphuretted hydrogen. 5. Mofettes; emanations of carbon-dioxide with nitrogen and oxygen, marking the last phase of volcanic activity.

[6] Neues Jahrb. 1878, p. 164.

while carbon-dioxide, sulphuretted hydrogen, and nitrogen occur at all the fumaroles, even where the temperature is not higher than that of the atmosphere.[7]

The following are the chief gases and acids evolved at volcanic fumaroles. Hydrochloric acid is abundant at Vesuvius, and probably at many other vents whence it has not been recorded. It is recognizable by its pungent, suffocating fumes, which make approach difficult to the clefts from which it issues. Sulphuretted hydrogen and sulphurous acid are distinguishable by their odors. The liability of the former gas to decomposition leads to the deposition of a yellow crust of sulphur; occasionally, also, the production of sulphuric acid is observed at active vents. From observations made at Vesuvius in May, 1878, Mr. Siemens concluded that vast quantities of free hydrogen or of combustible compounds of this gas exist dissolved in the magma of the earth's interior, and that these, rising and exploding in the funnels of volcanoes, give rise to the detonations and clouds of steam.[8] At the eruption of Santorin in 1866, the same gases were also distinctly recognized by Fouqué, who for the first time established the existence of true volcanic flames. These were again studied spectroscopically in the following year by Janssen, who found them to arise essentially from the combustion of free hydrogen, but with traces of chlorine, soda, and copper. Fouqué determined by analysis that, immediately over the focus of eruption, free hydrogen formed thirty per cent of the gases emitted, but that the proportion of this gas rapidly diminished with distance from the active vents and hotter lavas, while at the same time the proportion of marsh-gas and carbon-dioxide rapidly increased. The gaseous emanations collected by him were found to contain abundant free oxygen as well as hydrogen. One analysis gave the following results: carbon-dioxide 0·22, oxygen 21·11, nitrogen 21·90, hydrogen 56·70, marsh-gas 0·07=100·00. This gaseous mixture, on coming in contact with a burning body, at once ignites with a sharp explosion. Fouqué infers that the water-vapor of volcanic vents may exist in a state of dissociation within the molten magma whence lavas rise.[9] Carbon-dioxide rises

[7] "Santorin et ses éruptions," Paris, 1879.
[8] Monatsb. K. Preuss. Akad. 1878, p. 588.
[9] Fouqué, "Santorin et ses éruptions," p. 225.

chiefly (*a*) after an eruption has ceased and the volcano relapses into quiescence; or (*b*) after volcanic action has otherwise become extinct. Of the former phase, instances are on record at Vesuvius where an eruption has been followed by the emission of this gas so copiously from the ground as to suffocate hundreds of hares, pheasants, and partridges. Of the second phase, good examples are supplied by the ancient volcanic regions of the Eifel and Auvergne, where the gas still rises in prodigious quantities. Bischof estimated that the volume of carbonic acid evolved in the Brohl Thal amounts to 5,000,000 cubic feet, or 300 tons of gas in one day. Nitrogen, derived perhaps from the decomposition of atmospheric air dissolved in the water which penetrates into the volcanic foci, has been frequently detected among the gaseous emanations. At Santorin it was found to form from 4 to 88 per cent of the gas obtained from different fumaroles.[10] Fluorine and iodine have likewise been noticed.

With these gases and vapors are associated many substances which, sublimed by the volcanic heat or resulting from reactions among the escaping vapors, appear as Sublimates along crevices wherein they reach the air and are cooled. Besides sulphur, there are several chlorides (particularly that of sodium, and less abundantly those of potassium, iron, copper, and lead); also free sulphuric acid, sal-ammoniac, specular iron, oxide of copper, boracic acid, alum, sulphate of lime, felspars, pyroxene, and other substances. Carbonate of soda occurs in large quantities among the fumaroles of Etna. Sodium-chloride sometimes appears so abundantly that wide spaces of a volcanic cone, as well as of the newly erupted lava, are crusted with salt, which can even be profitably removed by the inhabitants of the district. Considerable quantities of chlorides, etc., may thus be buried between successive sheets of lava, and in long subsequent times may give rise to mineral springs, as has been suggested with reference to the saline waters which issue from volcanic rocks of Old Red Sandstone and Carboniferous age in Scotland.[11] The iron-chloride forms a bright yellow and reddish crust on the crater walls, as well as on loose stones on the slopes of the cone. Specular iron, from the decomposition of iron-chloride, forms abundantly as thin lamellæ

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[10] Fouqué, loc. cit.

[11] Proc. Roy. Soc. Edin. ix. p. 367.

in the fissures of Vesuvian lavas. In the spring of 1873 the author observed delicate brown filaments of tenorite (copper-oxide, CuO) forming in clefts of the crater of Vesuvius. They were upheld by the upstreaming current of vapor until blown off by the wind. Fouqué has described tubular vents in the lavas of Santorin with crystals of anorthite, sphene, and pyroxene, formed by sublimation. In the lava stalactites of Hawaii needle-like fibres of breislakite abound.

2. **Water.**—Abundant discharges of water accompany some volcanic explosions. Three sources of this water may be assigned: (1) from the melting of snow by a rapid accession of temperature previous to or during an eruption; this takes place from time to time on Etna, in Iceland, and among the snowy ranges of the Andes, where the cone of Cotopaxi is said to have been entirely divested of its snow in a single night by the heating of the mountain; (2) from the condensation of the vast clouds of steam which are discharged during an eruption; this undoubtedly is the chief source of the destructive torrents so frequently observed to form part of the phenomena of a great volcanic explosion; and (3) from the disruption of reservoirs of water filling subterranean cavities, or of lakes occupying crater-basins; this has several times been observed among the South American volcanoes, where immense quantities of dead fish, which inhabited the water, have been swept down with the escaping torrents. The volcano of Agua in Guatemala received its name from the disruption of a crater-lake at its summit by an earthquake in 1540, whereby a vast and destructive debacle of water was discharged down the slopes of the mountain.[12] In the beginning of the year 1817, an eruption took place at the large crater of Idjèn, one of the volcanoes of

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[12] For an account of this mountain see K. v. Seebach, Abh. Gesell. Wiss. Göttingen, xxxviii. (1892) p. 216.

Java, whereby a steaming lake of hot acid water was discharged with frightful destruction down the slopes of the mountain. After the explosion, the basin filled again with water, but its temperature was no longer high.[13]

In many cases, the water rapidly collects volcanic dust as it rushes down, and soon becomes a pasty mud; or it issues at first in this condition from the volcanic reservoirs after violent detonations. Hence arise what are termed mud-lavas, or aqueous lavas, which in many respects behave like true lavas. This volcanic mud eventually consolidates into one of the numerous forms of tuff, a rock which, as has been already stated (p. 238), varies greatly in the amount of its coherence, in its composition, and in its internal arrangement. Obviously, unless where subsequently altered, it cannot possess a crystalline structure like that of true lava. As a rule, it betrays its aqueous origin by more or less distinct evidence of stratification, by the multifarious pebbles, stones, blocks of rock, tree-trunks, branches, shells, bones, skeletons, etc., which it has swept along in its course and preserved within its mass. Sections of this compacted tuff may be seen at Herculaneum.[14] The *trass* of the Brohl Thal and other valleys in the Eifel district, referred to on p. 242, is another example of an ancient volcanic mud.

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[13] See Junghuhn's "Java." For an account of the volcanoes of the Sunda Island and Moluccas, see F. Scheider, Jahrb. Geol. Reichsanst. Vienna, xxxv. (1885), p. 1. Consult also for the Javanese volcanoes the works on Krakatoa quoted on p. 362.

[14] Mallet thought that the so-called "mud-lavas" of Herculaneum and Pompeii were not aqueous deposits (Journ. Roy. Geol. Soc. Ireland, IV. (1876), p. 144). But there seems no reason to doubt that while an enormous amount of ashes fell during the eruption of A.D. 79, there were likewise, especially in the later phases of eruption, copious torrents of water that mingled with the fine ash and became "mud-lavas." The sharpness of outline and the absence of any trace of abdominal distension in the molds of the human bodies found at Pompeii, probably show that these victims of the catastrophe were rapidly enveloped in a firm coherent matrix which could hardly have been mere loose dust. See H. J. Johnston-Lavis, Q. J. Geol. Soc. xl. p. 89.

3. **Lava.**—The term lava is applied generally to all the molten rocks of volcanoes.[15] The use of the word in this broad sense is of great convenience in geological descriptions, by directing attention to the leading character of the rocks as molten products of volcanic action, and obviating the confusion and errors which are apt to arise from an ill-defined or incorrect lithological terminology. Precise definitions of the rocks, such as those given above in Book II., can be added when required. A few remarks regarding some of the general lithological characters of lavas may be of service here; the behavior of the rocks in their emission from volcanic orifices will be described in § 2.

While still flowing or not yet cooled, lavas differ from each other in the extent to which they are impregnated with gases and vapors. Some appear to be saturated, others contain a much smaller gaseous impregnation; and hence arise important distinctions in their behavior (pp. 370–395). After solidification, lavas present some noticeable characters, then easily ascertainable. (1) Their average specific gravity may be taken as ranging between 2·37 and 3·22. (2) The heavier varieties contain much magnetic or titaniferous iron, with augite and olivine, their composition being basic, and their proportion of silica averaging about 45 to 55 per cent. In this group come the basalts, nepheline-lavas, and leucite-lavas. The lighter varieties contain commonly a minor proportion of metallic bases, but are rich in silica, their percentage of that acid ranging between 70 and 75. They are thus not basic but acid rocks. Among their more important varieties are the rhyolites and obsidians. Some intermediate varieties (trachytes, phonolites, and andesites) connect the acid and basic series. (3) Lavas differ much in structure and texture. (*a*) Some are entirely crystalline, consisting of an interlaced mass of crystals and crystalline particles, as in some dolerites, and granitoid rhyolites. Even quartz, which used to be considered a non-volcanic mineral, charac-

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[15] "Alles ist Lava was im Vulkane fliesst und durch seine Flüssigkeit neue Lagerstätter einnimmt" is Leopold von Buch's comprehensive definition.

teristic of the older and chiefly of the plutonic eruptive rocks, has been observed in large crystals in modern lava (liparite and quartz-andesite[16]). (*b*) Some show more or less of a half-glassy or stony (devitrified) matrix, in which the constituent crystals are imbedded; this is the most common arrangement. (*c*) Others are entirely vitreous, such crystals or crystalline particles as occur in them being quite subordinate, and, so to speak, accidental inclosures in the main glassy mass. Obsidian or volcanic glass is the type of this group. (*d*) They further differ in the extent to which minute pores or larger cellular spaces have been developed in them. According to Bischof, the porosity of lavas depends on their degree of liquidity, a porous lava or slag, when reduced in his fusion-experiments to a thin-flowing consistency, hardening into a mass as compact as the densest lava or basalt.[17] The presence of interstitial steam in lavas, by expanding the still molten stone, produces an open cellular texture, somewhat like that of sponge or of bread. Such a vesicular arrangement very commonly appears on the upper surface of a lava current, which assumes a slaggy or cindery aspect. In some forms of pumice the proportion of air cavities is 8 or 9 times that of the inclosing glass. (4) Lavas vary greatly in color and general external aspect. The heavy basic kinds are usually dark gray, or almost black, though, on exposure to the weather, they acquire a brown tint from the oxidation and hydration of their iron. Their surface is commonly rough and ragged, until it has been sufficiently decomposed by the atmosphere to crumble into soil which, under favorable circumstances, supports a luxuriant vegetation. The less dense lavas, such as phonolites and trachytes, are frequently paler in color, sometimes yellow or buff, and decompose into light soils; but the obsidians present rugged black sheets of rock, roughened with ridges and heaps of gray froth-like pumice. Some of the most brilliant surfaces of color in any rock-scenery on the globe are to be found among volcanic rocks. The walls of active craters glow with endless hues of red and yellow. The Grand Cañon of the Yellowstone River has been dug out of the most marvellously tinted lavas and tuffs.

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[16] Wolf, Neues Jahrb. 1874, p. 377.

[17] "Chem. und Phys. Geol." supp. (1871), p. 144. On the production of the vesicular structure consult Dana, "Characteristics of Volcanoes," p. 161. Compare also Judd, Geol. Mag. 1888, p. 7.

4. **Fragmentary Materials.**—Under this title may be included all the substances which, driven up into the air by volcanic explosions, fall in solid form to the ground—the dust, ashes, sand, cinders, and blocks of every kind which are projected from a volcanic orifice. These materials differ in composition, texture, and appearance, even during a single eruption, and still more in successive explosions of the same volcano. For the sake of convenience, separate names are applied to some of the more distinct varieties, of which the following may be enumerated.

(1) Ashes and sand.—In many eruptions, vast quantities of an exceedingly fine light gray powder are ejected. As this substance greatly resembles what is left after a piece of wood or coal is burned in an open fire, it has been popularly termed *ash*, and this name has been adopted by geologists. If, however, by the word ash, the result of combustion is implied, its employment to denote any product of volcanic action must be regretted, as apt to convey a wrong impression. The fine ash-like dust ejected by a volcano is merely lava in an extremely fine state of comminution. So minute are the particles that they find their way readily through the finest chinks of a closed room, and settle down upon floor and furniture, as ordinary dust does when a house is shut up. From this finest form of material, gradations may be traced, through what is termed volcanic sand, into the coarser varieties of ejected matter. In composition, the ash and sand vary necessarily with the nature of the lava from which they are derived. Their microscopic structure, and especially their abundant microlites, crystals, and volcanic glass, have been already referred to (pp. 239–241).

(2) Lapilli or rapilli (p. 239) are ejected fragments ranging from the size of a pea to that of a walnut; round, subangular, or angular in shape, and having the same indefinite range of composition as the finer dust. As a rule, the larger pieces fall nearest the focus of eruption. Sometimes they are solid fragments of lava, but more usually they have a cellular texture, while sometimes they are so light and porous as to float readily on water, and, when ejected near the sea, to cover its surface. Well-formed crystals occur in the lapilli of many volcanoes, and are also ejected separately.

It has been observed indeed that the fragmentary materials not infrequently contain finer crystals than the accompanying lava.[18]

(3) Volcanic Blocks (p. 239) are larger pieces of stone, often angular in shape. In some cases they appear to be fragments loosened from already solidified rocks in the chimney of the volcano. Hence we find among them pieces of non-volcanic rocks, as well as of older tuffs and lavas recognizably belonging to early eruptions. In many cases, they are ejected in enormous quantities during the earlier phases of violent eruption. The great explosion from the side of Ararat in 1840 was accompanied by the discharge of a vast quantity of fragments over a space of many square miles around the mountain. Whitney has described the occurrence in California of beds of such fragmentary volcanic breccia, hundreds of feet thick and covering many square miles of surface. Junghuhn, in his account of the eruption in Java in 1772, mentions that a valley ten miles long was filled to an average depth of fifty feet with angular volcanic débris.[19]

Among the earlier eruptions of a volcano, fragments of the rocks through which the vent has been drilled may frequently be observed. These are in many cases not volcanic. Blocks of schist and granitoid rocks occur in the cinder-beds at the base of the volcanic series of Santorin. In the older tuffs of Somma, pieces of altered limestone (sometimes measuring 200 cubic feet or more and weighing upward of 15 tons) are abundant and often contain cavities lined with the characteristic "Vesuvian minerals."[20] Blocks of a coarsely crystalline granitoid (but really trachytic) lava have been particularly observed both on Etna[21] and Vesuvius. In the year 1870 a mass of that kind, weighing several tons, was to be seen lying at the foot of the upper cone of Vesuvius, within the entrance to the Atrio del Cavallo. Similar blocks occur among the Carboniferous volcanic pipes of central Scotland, together sometimes with fragments of sandstone, shale, or limestone, not infrequently full of Carboniferous fossils.[22] Enormous masses of various

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[18] Sartorius von Waltershausen, "Sicilien und Island," 1853, p. 328.

[19] But see the remarks already made on volcanic conglomerate, ante, p. 283.

[20] See H. J. Johnston-Lavis, Q. J. Geol. Soc. xl. p. 75.

[21] For the erupted blocks (Auswürflinge) of Etna see "Der Aetna," ii. pp. 216, 330, 461.

[22] Trans. Roy. Soc. Edin. xxix. p. 459. See postea, Book IV. Sect. vii. § 1, 4.

schists have been carried up by the lavas of the Tertiary volcanic plateau of the Inner Hebrides.[23]

(4) Volcanic Bombs and slags.—These have originally formed portions of the column of lava ascending the pipe of a volcano, and have been detached and hurled into the air by successive explosions of steam. A bomb (Fig. 41) is a round, elliptical, or pear-shaped, often discoidal mass of lava, from a few inches to several feet in diameter; sometimes tolerably solid throughout, more usually coarsely cellular inside. Not infrequently its interior is hollow, and the bomb then consists of a shell which is most close-grained

Fig. 41.—Section of Volcanic Bomb, one-third natural size.

toward the outside, or the centre is a block of stone with an external coating of lava. There can be no doubt that, when torn by eructations of steam from the surface of the boiling lava, the material of these bombs is in as thoroughly molten a condition as the rest of the mass. From the rotatory motion imparted by its ejection, it takes a circular form, and in proportion to its rapidity of rotation and fluidity is the amount of its "flattening at the poles." The centrifugal force within allows the expansion of the interstitial vapor, while the outer surface rapidly cools and solidifies; hence the solid crust, and the porous or cavernous interior. Such bombs, varying from the size of an apple to that of a man's body, were found by Darwin abundantly strewn over the ground in the Island of Ascension; they were also ejected

[23] Trans. Roy Soc. Edin. xxxv. (1888), p. 82.

in vast quantities during the eruption of Santorin in 1866.[24] Among the tuffs of the Eifel region, small bombs, consisting mostly of granular olivine, are of common occurrence, as also pieces of sanidine or other less fusible minerals which have segregated out of the magma before ejection. In like manner, among the tuffs filling volcanic necks, probably of Permian age, which pierce the Carboniferous rocks of Fife, large worn crystals of orthoclase, biotite, etc., are found. When the ejected fragment of lava has a rough irregular form and a porous structure, like the clinker of an iron furnace, it is known as a slag.[25]

The fragmentary materials erupted by a volcano and deposited around it acquire by degrees more or less consolidation, partly from the mere pressure of the higher upon the lower strata, partly from the influence of infiltrating water. It has been already stated (p. 240) that different names are applied to the rocks thus formed. The coarse, tumultuous, unstratified accumulation of volcanic débris within a crater or funnel is called Agglomerate. When the débris, though still coarse, is more rounded, and is arranged in a stratified form on the slopes of the cone or on the country beyond, it becomes a Volcanic Conglomerate. The finer-grained varieties, formed of dust and lapilli, are included in the general designation of Tuffs. These are usually pale yellowish, grayish, or brownish, sometimes black rocks, granular, porous, and often incoherent in texture. They occur interstratified with and pass into ordinary non-volcanic sediment.

Organic remains sometimes occur in tuff. Where volcanic débris has accumulated over the floor of a lake, or of the sea, the entombing and preserving of shells and other organic objects must continually take place. Examples of this kind are cited in later pages of this work from older geological formations. Professor Guiscardi of Naples found about 100 species of marine shells of living species in the old tuffs of Vesuvius. Marine shells have been picked up within the crater of Monte Nuovo, and have been frequently observed in the old or marine tuff of that district. Showers of ash, or sheets of volcanic mud, often preserve land-shells, insects, and vegetation living on the area at the time. The

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[24] Darwin, "Geological Observations on Volcanic Islands," 2d edit. p. 42. Fouqué, "Santorin," p. 79.

[25] On the ratio between the pores and volume of the rock in slags and lavas, see determinations by Bischof, "Chem. und Phys. Geol." supp. (1871), p. 158.

older tuffs of Vesuvius have yielded many remains of the shrubs and trees which at successive periods have clothed the flanks of the mountain. Fragments of coniferous wood, which once grew on the tuff-cones of Carboniferous age in central Scotland, are abundant in the "necks" of that region, while the minute structure of some of the lepidodendroid plants has also been admirably preserved there in tuff.[26]

§ 2. Volcanic Action

Volcanic action many be either constant or periodic. Stromboli, in the Mediterranean, so far as we know, has been uninterruptedly emitting hot stones and steam, from a basin of molten lava, since the earliest period of history.[27] Among the Moluccas, the volcano Sioa, and in the Friendly Islands, that of Tofua, have never ceased to be in eruption since their first discovery. The lofty cone of Sangay, among the Andes of Quito, is always giving off hot vapors; Cotopaxi, too, is ever constantly active.[28] But, though examples of unceasing action may thus be cited from widely different quarters of the globe, they are nevertheless exceptional. The general rule is that a volcano breaks out from time to time with varying vigor, and after longer or shorter intervals of quiescence.

Active, Dormant, and Extinct Phases.—It is usual to class volcanoes as *active*, *dormant*, and *extinct*. This arrangement, however, often presents considerable difficulty in its application. An active volcano cannot of course be mistaken, for even when not in eruption, it shows by its discharge of

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[26] Trans. Roy. Soc. Edin. xxix. p. 470; postea, Book IV. Part VII. Sect. ii. § 2.

[27] For accounts of Stromboli see Spallanzani's "Voyages dans les deux Siciles." Scrope's "Volcanoes." Judd, Geol. Mag. 1875., Mercalli's "Vulcani," etc. p. 135; and his papers in Atti Soc. Ital. Sci. Nat. xxii., xxiv., xxvii., xxix., xxxi. L. W. Fulcher, Geol. Mag. 1890, p. 347.

[28] For descriptions of Cotopaxi, see Wolf, Neues Jahrb. 1878; Whymper, Nature, xxiii. p. 323; "Travels amongst the Great Andes," chap. vi.

steam and hot vapors that it might break out into activity at any moment. But in many cases, it is impossible to decide whether a volcano should be called extinct or only dormant. The volcanoes of Silurian age in Wales, of Carboniferous age in Ireland, of Permian age in the Harz, of Miocene age in the Hebrides, of younger Tertiary age in the Western States and Territories of North America, are certainly all extinct. But the older Tertiary volcanoes of Iceland are still represented there by Skaptar-Jökull, Hecla, and their neighbors.[29] Somma, in the first century of the Christian era, would have been naturally regarded as an extinct volcano. Its fires had never been known to have been kindled; its vast crater was a wilderness of wild vines and brushwood, haunted, no doubt, by wolf and wild boar. Yet in a few days, during the autumn of the year 79, the half of the crater walls was blown out by a terrific series of explosions, the present Vesuvius was then formed within the limits of the earlier crater, and since that time volcanic action has been intermittently exhibited up to the present day. Some of the intervals of quietude, however, have been so considerable that the mountain might then again have been claimed as an extinct volcano. Thus, in the 131 years between 1500 and 1631, so completely had eruptions ceased that the crater had once

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[29] On the volcanic phenomena of Iceland consult G. Mackenzie's "Travels in the Island of Iceland during the Summer of 1810." E. Henderson's "Iceland." Zirkel, "De geognostica Islandæ constitutione observationes," Bonn, 1861. Thoroddsen, "Oversigt over de islandske Vulkaners Historie," translated in resumé by G. H. Boehmer, Smithsonian Inst. Rep. 1885, part i. p. 495; also Bihang t. Svensk. Vet. Akad. Handl. 14, ii. (1888), 17, ii. (1891); Geol. Mag. 1880, p. 458; Nature, Oct. 1884. Mitth. K. K. Geogr. Ges. Vienna, xxiv. (1891), p. 117. Keilhack, Zeitsch. Deutsch. Geol. Gesel. xxxviii. (1886), p. 376; Schmidt, op. cit. xxxvii. (1885), p. 737; A. Helland, "Lakis Kratere og Lava-ströme," Universitets Programme, Christiania, 1885; Bréon, "Géologie de l'Islande, et des Iles Foeroe," Paris, 1884; T. Anderson, Journ. Soc. Arts, vol. xl. (1892), p. 397.

more become choked with copsewood. A few pools and springs of very salt and hot water remained as memorials of the former condition of the mountain. But this period of quiescence closed with the eruption of 1631—the most powerful of all the known explosions of Vesuvius, except the great one of 79. In the island of Ischia, Mont' Epomeo was last in eruption in the year 1302, its previous outburst having taken place, it is believed, about seventeen centuries before that date. From the craters of the Eifel, Auvergne, the Vivarais and central Italy, though many of them look as if they had only recently been formed, no eruption has been known to come during the times of human history or tradition. In the west of North America, from Arizona to Oregon, numerous stupendous volcanic cones occur, but even from the most perfect and fresh of them nothing but steam and hot vapors has yet been known to proceed.[30] But the presence there of hot springs and geysers proves the continued existence of one phase of volcanic action.

In short, no essential distinction can be drawn between dormant and extinct volcanoes. Volcanic action, as will be afterward pointed out, is apt to show itself again and again, even at vast intervals, within the same regions and over the same sites. The dormant or waning condition of a volcano, when only steam and various gases and sublimates are given off, is sometimes called the Solfatara phase, from the well-known dormant crater of that name near Naples.

Sites of Volcanic Action.—Volcanoes may break through any geological formation. In Auvergne, in the Miocene period, they burst through the granitic and gneissose plateau of central France. In Lower Old Red Sandstone

[30] Eruptions occurred perhaps less than 100 years ago. Diller, Bull. U. S. Geol. Surv., No. 79.

times, they pierced contorted Silurian rocks in central Scotland. In late Tertiary and post-Tertiary ages, they found their way through recent soft marine strata, and formed the huge piles of Etna, Somma, and Vesuvius; while in North America, during the same cycle of geological time, they flooded with lava and tuff many of the river-courses, valleys, and lakes of Nevada, Utah, Wyoming, Idaho, and adjacent territories. On the banks of the Rhine, at Bonn and elsewhere, they have penetrated some of the older alluvia of that river. In many instances, also, newer volcanoes have appeared on the sites of older ones. In Scotland, the Carboniferous volcanoes have risen on the ruins of those of the Old Red Sandstone, those of the Permian period have broken out among the earlier Carboniferous eruptions, while the older Tertiary dikes have been injected into all these older volcanic masses. The newer *puys* of Auvergne were sometimes erupted through much older and already greatly denuded basalt-streams. Somma and Vesuvius have risen out of the great Neapolitan plain of older marine tuff, while in central Italy newer cones have been thrown up upon the wide Roman plain of more ancient volcanic débris.[31] The vast Snake River lava-fields of Idaho overlie denuded masses of earlier trachytic lavas, and similar proofs of a long succession of intermittent and widely-separated volcanic outbursts can be traced northward into the Yellowstone Valley.

When a volcanic vent is opened, it might be supposed always to find its way to the surface along some line of fis-

[31] According to Prof. G. Pozzi, the principal volcanic outbursts of Italy are of the Glacial Period. Atti Lincei, 3d ser. vol. ii. (1878), p. 35. Stefani regards those of Tuscany as partly Miocene, partly Pliocene and post-Pliocene. (Proc. Tosc. Soc. Nat. Pisa, 1. p. xxi.)

sure, valley, or deep depression. No doubt many, if not most, modern as well as ancient vents, especially those of large size, have done so. It is a curious fact, however, that in innumerable instances minor vents have appeared where there was no visible line of dislocation in the rocks at the surface to aid them. This has been well shown by a study of the ancient volcanic rocks of the Old Red Sandstone, Carboniferous, and Permian formations of Scotland.[32] It has likewise been most impressively demonstrated by the way in which the minor basalt cones and craters of Utah have broken out near the edges or even from the face of cliffs, rather than at the bottom. Captain Dutton remarks that among the high plateaus of Utah, where there are hundreds of basaltic craters, the least common place for them is at the base of a cliff, and that, though they occur near faults, it is almost always on the lifted, rarely upon the depressed side.[33] On a small scale, a similar avoidance of the valley bottom is shown on the Rhine and Moselle, where eruptions have taken place close to the edge of the plateau through which these rivers wind. Why outbreaks should have occurred in this way is a question not easily answered. It suggests that the existing depressions and heights of the earth's surface may sometimes be insignificant features, compared with the depth of the sources of volcanoes and the force employed in volcanic eruption. On the other hand, it is remarkable that in Scotland the Palæozoic eruptions took place on the low ground and valleys, and continued to show themselves there during a long succession of volcanic periods. Especially noteworthy is the way in which the Permian vents were

[32] Trans. Roy. Soc. Edin. xxix. p. 437.
[33] "High Plateaus of Utah," Geol. and Geog. Survey of Territories, 1880, p. 62.

opened in lines and groups along the bottom of long narrow valleys in the Silurian uplands.[34]

Ordinary phase of an active Volcano.—The interval between two eruptions of an active volcano shows a gradual augmentation of energy. The crater, emptied by the last discharge, has its floor slowly upraised by the expansive force of the lava-column underneath. Vapors rise in constant outflow, accompanied sometimes by discharges of dust or stones. Through rents in the crater-floor red-hot lava may be seen only a few feet down. Where the lava is maintained at or above its fusion-point and possesses great liquidity, it may form boiling lakes, as in the great crater of Kilauea, where acres of seething lava may be watched throwing up fountains of molten rock, surging against the walls and re-fusing large masses that fall into the burning flood. The lava-column inside the pipe of a volcano is all this time gradually rising, until some weak part of the wall allows it to escape, or until the pressure of the accumulated vapors becomes great enough to burst through the hardened crust of the crater-floor and give rise to the phenomena of an eruption.

Conditions of Eruption.—Leaving for the present the general question of the cause of volcanic action, it may be here remarked that the conditions determining any particular eruption are still unknown. The explosions of a volcano may be to some extent regulated by the conditions of atmospheric pressure over the area at the time. In the case of a volcanic funnel like Stromboli, where, as Scrope pointed out, the expansive subterranean force within, and the repressive effect of atmospheric pressure without, just balance

[34] Quart Journ. Geol. Soc. vol. xlviii. (1892). Presidential Address, p. 156.

each other, any serious disturbance of that pressure might be expected to make itself evident by a change in the condition of the volcano. Accordingly, it has long been remarked by the fishermen of the Lipari Islands that in stormy weather there is at Stromboli a more copious discharge of steam and stones than in fine weather. They make use of the cone as a weather-glass, the increase of its activity indicating a falling, and the diminution a rising barometer. In like manner, Etna, according to Sartorius von Waltershausen, is most active in the winter months. Mr. Coan has indicated a relation between the eruptions of Kilauea and the rainy seasons of Hawaii, most of the discharges of that crater taking place within the four months from March to June.[35]

When we remember the connection, now indubitably established, between a more copious discharge of fire-damp in mines and a lowering of atmospheric pressure, we may be prepared to find a similar influence affecting the escape of vapors from the upper surface of the lava-column of a volcano; for it is not so much to the lava itself as to the expansive vapors impregnating it that the manifestations of volcanic activity are due. Among the Vesuvian eruptions since

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[35] Dana, "Characteristics of Volcanoes," p. 125. For accounts of the volcanic phenomena of Hawaii, see W. Ellis, "Polynesian Researches." Wilkes' U. S. Exploring Expedition, 1838–42, "Geology," by J. D. Dana. The Rev. T. Coan, a missionary resident in Hawaii, observed the operations of the volcanoes for upward of forty years, and published from time to time short notices of them in the American Journal of Science, vols. xiii. (1852) xiv., xv., xviii., xxi., xxii., xxiii., xxv., xxvii., xxxvii., xl., xliii., xlvii., xlix; 3d ser. ii. (1871) iv., vii., viii., xiv., xviii., xx., xxi., xxii. (1881). Prof. Dana has recently revisited these volcanoes and fully discussed their phenomena in the Amer. Journ. Sci. vols. xxxiii.-xxxvii. (1887–89), and in his "Characteristics of Volcanoes." See also C. E. Dutton, Amer. Journ. Sci. xxv. (1883), p. 219; Report U. S. Geological Survey, 1882–83. L. Green, "Vestiges of the Molten Globe," 1887. For an account of the remarkable glassy lavas of Hawaii, see E. Cohen, Neues Jahrb. 1880 (ii.), p. 23; and a general account of the petrography of the islands, by E. S. Dana, Amer. Journ. Sci. xxxvii. (1889), p. 441.

the middle of the seventeenth century, the number which took place in winter and spring has been to that of those which broke out in summer and autumn as 7 to 4. In Japan, also, the greater number of recorded eruptions have taken place during the cold months of the year, February to April.[36]

There may be other causes besides atmospheric pressure concerned in these differences; the preponderance of rain during the winter and spring may be one of these. According to Mr. Coan, previous to the great Hawaiian eruption of 1868 there had been unusually wet weather, and to this fact he attributes the exceptional severity of the earthquakes and volcanic explosions. The greater frequency of Japanese volcanic eruptions and earthquakes in winter has been referred in explanation to the fact that the average barometric gradient across Japan is steeper in winter than in summer, while the piling up of snow in the northern regions gives rise to long-continued stresses, in consequence of which certain lines of weakness in the earth's crust are more prepared to give way during the winter months than they are in summer.[37] The effects of varying atmospheric pressure, however, can probably only slightly and locally modify volcanic activity. Eruptions, like the great one of Cotopaxi in 1877, have in innumerable instances taken place without, so far as can be ascertained, any reference to atmospheric conditions.

Kluge has sought to trace a connection between the years of maximum and minimum sun-spots and those of greatest and feeblest volcanic activity, and has constructed lists to show that years which have been specially characterized by terrestrial eruptions have coincided with those marked by

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[36] J. Milne, Seismol. Soc. Japan, IX. Part ii. p. 174.
[37] J. Milne, loc. cit.

few sun-spots and diminished magnetic disturbance.[38] Such a connection cannot be regarded as having yet been satisfactorily established. Again, the same author has called attention to the frequency and vigor of volcanic explosions at or near the time of the August meteoric shower. But in this case, likewise, the cited examples can hardly yet be looked upon as more than coincidences.

Periodicity of Eruptions.—At many volcanic vents the eruptive energy manifests itself with more or less regularity. At Stromboli, which is constantly in an active state, the explosions occur at intervals varying from three or four to ten minutes and upward. A similar rhythmical movement has been often observed during the eruptions at other vents which are not constantly active. Volcano, for example, during its eruption of September, 1873, displayed a succession of explosions which followed each other at intervals of from twenty to thirty minutes. At Etna and Vesuvius a similar rhythmical series of convulsive efforts has often been observed during the course of an eruption.[39] Among the volcanoes of the Andes a periodic discharge of steam has been observed; Mr. Whymper noticed outrushes of steam to proceed at intervals of from twenty to thirty minutes from the summit of Sangai, while during his inspection of the great crater of Cotopaxi, this volcano was seen to blow off steam at intervals of about half an hour.[40] At the eruption of the Japanese volcano, Oshima, in 1877, Mr. Milne observed that the explosions occurred nearly every two seconds, with occa-

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[38] "Ueber Synchronismus und Antagonismus," 8vo, Leipzig, 1863, p. 72. A. Poëy (Comptes Rend. lxxviii. (1874), p. 51) believes that among the 786 eruptions recorded by Kluge, between 1749 and 1861, the maxima correspond to periods of minimum in solar spots. See, however, postea, p. 477.

[39] G. Mercalli, Atti. Soc. Ital. Sci. Nat. xxiv. (1881).

[40] "Travels amongst the Great Andes of the Equator," 1892, pp. 74, 153.

sional pauses of 15 or 20 seconds.[41] Kilauea, in Hawaii, seems to show a regular system of grand eruptive periods. Dana has pointed out that outbreaks of lava have taken place from that volcano at intervals of from eight to nine years, this being the time required to fill the crater up to the point of outbreak, or to a depth of 400 or 500 feet.[42]

Some volcanoes have exhibited a remarkable paroxysmal phase of activity, when after comparative or complete quiescence a sudden gigantic explosion has taken place, followed by renewed and prolonged repose. Vesuvius supplies the most familiar illustration of this character of volcanic energy. The great eruption of A.D. 79, which truncated the upper part of the old cone of Somma, was a true paroxysmal explosion, unlike anything that had preceded it within historic times, and far more violent than any subsequent manifestation of the same volcano. The crater-basin of Santorin, of which the islands Thera and Therasia represent portions of the rim, seems to have been blown out by some stupendous paroxysm in prehistoric times. The vast explosion of Krakatoa in 1883 was another memorable example. In these instances there was an earlier period of ordinary volcanic activity, during which a large cone was gradually built up. In the case of Somma and Krakatoa the energy died down for a time, and the paroxysm came with hardly any premonitory warning. It has been succeeded by a time of comparatively feeble activity. At Vesuvius the great explosion of 1631, which terminated nearly 1500 years of quiescence, may be regarded as a minor paroxysm, since which the mountain has remained more continuously active.

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[41] Trans. Seism. Soc. Japan, ix. part ii. p. 82.

[42] "Characteristics of Volcanoes," p. 124. On periodicity of eruptions, see Kluge, Neues Jahrb. 1862, p. 582.

General sequence of events in an Eruption.—The approach of an eruption is not always indicated by any premonitory symptoms, for many tremendous explosions are recorded to have taken place in different parts of the world without perceptible warning. Much in this respect would appear to depend upon the condition of liquidity of the lava, and the amount of resistance offered by it to the passage of the escaping vapors through its mass. In Hawaii, where the lavas are remarkably liquid, vast outpourings of them have taken place quietly without earthquakes during the present century. But even there, the great eruption of 1868 was accompanied by violent earthquakes.

The eruptions of Vesuvius are often preceded by failure or diminution of wells and springs. But more frequent indications of an approaching outburst are conveyed by sympathetic movements of the ground. Subterranean rumblings and groanings are heard; slight tremors succeed, increasing in frequency and violence till they become distinct earthquake shocks. The vapors from the crater grow more abundant, as the lava-column in the pipe or funnel of the volcano ascends, forced upward and kept in perpetual agitation by the passage of elastic vapors through its mass. After a long previous interval of quiescence, there may be much solidified lava toward the top of the funnel, which will restrain the ascent of the still molten portion underneath. A vast pressure is thus exercised on the sides or the cone, which, if too weak to resist, will open in one or more rents, and the liquid lava will issue from the outer slope of the mountain; or the energies of the volcano will be directed toward clearing the obstruction in the chief throat, until with tremendous explosions, and the rise of a vast cloud of dust and fragments, the bottom and sides of the crater are finally blown out, and the top of the cone disappears. The lava may now escape from the lowest part of the lip of the crater, while, at the same time, immense numbers of red-hot bombs, scoriæ, and stones are shot up into the air. The lava at first rushes down like one or more rivers of melted iron, but, as it cools, its rate of motion lessens. Clouds of steam rise from its surface, as well as from the central crater. Indeed, every successive paroxysmal convulsion of the mountain is marked, even at a distance, by the rise of huge ball-like wreaths or clouds of steam, mixed with dust and stones, forming a column which towers sometimes a couple of miles or more above the summit of the cone. By degrees these eructations diminish in frequency and intensity. The lava ceases to issue, the showers of stones and dust decrease, and after a time, which may vary from hours to days or months, even in the *régime* of the same mountain, the volcano becomes once more tranquil.[43]

In the investigation of the subject, the student will naturally devote attention specially to those aspects of volcanic action which have more particular geological interest from the permanent changes with which they are connected, or from the way in which they enable us to detect and realize conditions of volcanic energy in former periods.

Fissures.—The convulsions which culminate in the formation of a volcano usually split open the terrestrial crust by a more or less nearly rectilinear fissure, or by a system of fissures. In the subsequent progress of the mountain, the ground at and around the focus of action is liable to be again and again rent open by other fissures. These tend to di-

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[43] See Schmidt's narrative of the eruption of Vesuvius in May, 1855 (ante, p. 333). An account of the great eruption of Cotopaxi in June, 1877, by Dr. Th. Wolf, will be found in Neues Jahrb. 1878, p. 113.

verge from the focus; but around the vent where the rocks have been most exposed to concussion, the fissures sometimes intersect each other in all directions. In the great eruption of Etna, in the year 1669, a series of six parallel fissures opened on the side of the mountain. One of these, with a width of two yards, ran for a distance of 12 miles, in a somewhat winding course, to within a mile of the top of the cone.[44] Similar fissures, but on a smaller scale, have often been observed on Vesuvius and other volcanoes.[45] A fissure sometimes reopens for a subsequent eruption.

Two obvious causes may be assigned for the pushing upward of a crater-floor and the fissuring of a volcanic cone—(1) the enormous pressure of the dissolved vapors or gases acting upon the walls and roof of the funnel and convulsing the cone by successive explosions; and (2) the hydrostatic pressure of the lava-column in the funnel, which may be taken to be about 120 lbs. per square inch, or nearly 8 tons on the square foot, for each 100 feet of depth. Both of these causes may act simultaneously, and their united effect has been to uplift enormous superincumbent masses of solid rock and to produce a widespread series of long and continuous fissures reaching from unknown depths to various distances from the surface and even opening up sometimes on the surface. These results of the expansive energy of volcanic action are of special interest to the geologist, for he encounters evidence of similar operations in former times preserved in the crust of the earth (see Book IV. Part VII. Sect. i.).

Into rents thus formed, the water-substance or vapor

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[44] For fissures on Etna, see Silvestri, Boll. R. Geol. Com. Ital. 1874.

[45] For a description of those of Iceland (which run chiefly N.E. to S.W., and N. to S.) see T. Kjerulf, Nyt. Mag. xxi. 147.

rises with great expansive force, followed by the lava which solidifies there like iron in a mold. Where fissures are vertical or highly inclined the igneous rock takes the form of *dikes* or *veins*; where the intruded material has forced its way more or less in a horizontal direction between strata of tuff, beds of non-volcanic sediments, or

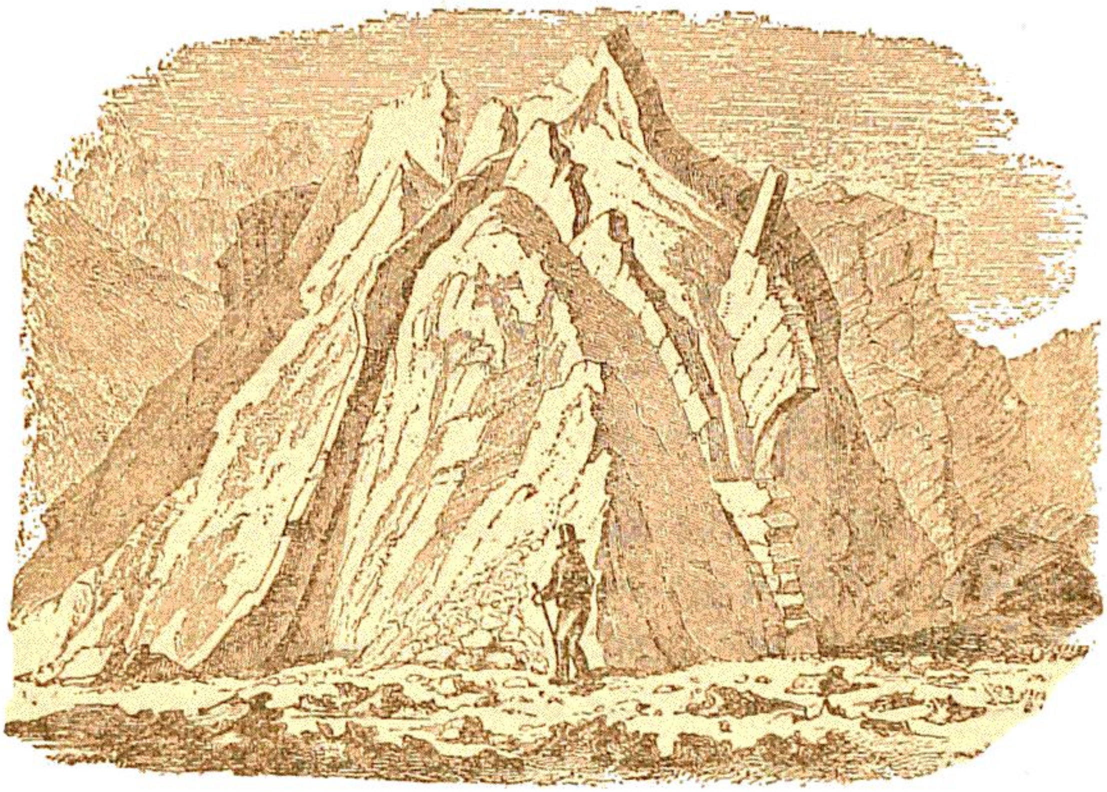

Fig. 42.—View of Lava-dikes, Valle del Bove, Etna (Abich).

flows of lava, it takes the form of *sheets* (*sills*) or *beds*. The cliffs of many an old crater show how marvellously they have been injected by such veins, dikes, or sheets of lava. Those of Somma, and the Valle del Bove on Etna (Fig. 42), which have long been known, project now from the softer tuffs like walls of masonry.[46] The crater cliffs of Santorin also present an abundant series of dikes. The permanent separation of the walls of fissures by the consolidation of the lava that rises in them as dikes must widen the dimen-

[46] S. von Waltershausen "Der Aetna," ii. p. 341.

sions of a cone, for the fissures are not due to shrinkage, although doubtless the loosely piled fragmentary materials, in the course of their consolidation, develop lines of joint. Sometimes the lava has evidently risen in a state of extreme fluidity, and has at once filled the rents prepared for it,

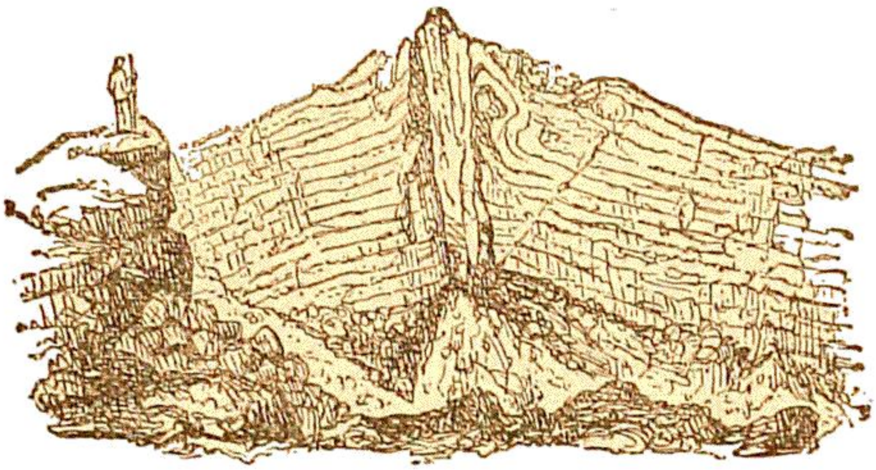

Fig. 43.—Dike contorting beds of tuff. Crater of Vesuvius (Abich).

cooling rapidly on the outside as a true volcanic glass, but assuming a distinctly crystalline structure inside (*ante*, p. 296). Dikes of this kind, with a vitreous crust on their sides, may be seen on the crater-wall of Somma, and not uncommonly among basalt dikes in Iceland and Scotland. In other cases, the lava had probably already acquired a more viscous or even lithoid character ere it rose in the fissure, and in this condition was able to push aside and even contort the strata of tuff through which it made its way (Fig. 43). There can be little doubt that in the architecture of a volcano, dikes must act the part of huge beams and girders (Fig. 44), binding the loose tuffs and intercalated lavas together, and strengthening the cone against the effects of subsequent convulsions.

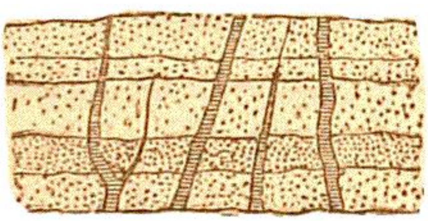

Fig. 44.—Section of Dikes of Lava traversing the bedded tuffs of a volcanic cone.

From this point of view, an explanation suggests itself of the observed alternations in the character of a volcano's eruptions. These alternations may depend in great measure upon the relation between the height of the cone, on the one hand, and the strength of its sides, on the other. When the sides have been well braced together by interlacing dikes, and further thickened by the spread of volcanic materials all over their slopes, they may resist the effects of explosion and of the pressure of the ascending lava-column. In this case, the volcano may find relief only from its summit, and if the lava flows forth, it will do so from the top of the cone. As the cone increases in elevation, however, the pressure from within upon its sides augments. Eventually egress is once more established on the flanks by means of fissures, and a new series of lava-streams is poured out over the lower slopes (see Fig. 62).

In the deeper portions of a volcanic vent the convulsive efforts of the lava-column to force its way upward must often produce lateral as well as vertical rifts, and into these the molten material will rush, exerting as it goes an enormous upward pressure on the mass of rock overlying it. At a modern volcano these subterranean manifestations cannot be seen, but among the volcanoes of Tertiary and older time they have been revealed by the progress of denudation. Some of these older examples teach us the prodigious upheaving power of the sheets of molten rock intruded between volcanic or other strata. An account of this structure (sills, laccolites), with reference to some examples of it, will be found in Book IV. Part VII.[47]

Though lava very commonly issues from the lateral

[47] See particularly the description of intrusive sheets or laccolites.

fissures on a volcanic cone, it may sometimes approach the surface in them without actually flowing out. The great fissure on Etna in 1669, for example, was visible even from a distance, by the long line of vivid light which rose from the incandescent lava within. Again, it frequently happens that minor volcanic cones are thrown up on the line of a fissure, either from the congelation of the lava round the point of emission, or from the accumulation of ejected scoriæ round the fissure-vent. One of the most remarkable examples of this kind is that of the Laki fissure in Iceland, the whole length of which (12 miles) bristles with small cones and craters almost touching each other.[48]

Explosions.—Apart from the appearance of visible fissures, volcanic energy may be, as it were, concentrated on a given point, which will usually be the weakest in the structure of that part of the terrestrial crust, and from which the solid rock, shattered into pieces, is hurled into the air by the enormous expansive energy of the volcanic vapors.[49] This operation has often been observed in volcanoes already formed, and has even been witnessed on ground previously unoccupied by a volcanic vent. The history of the cone of Vesuvius brings before us a long series of such explosions, beginning with that of A.D. 79, and coming down to the present day (Fig. 45). Even now, in spite of all the lava and ashes poured out during the last eighteen centuries, it is easy to see how stupendous must have been that earliest explosion, by which the southern half of the ancient crater was blown out. At every suc-

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[48] A. Helland, "Lakis Kratere og Lava-ströme," cited on p. 345. On this straight fissure some 500 craters rise, varying from 5 to 450 feet high.

[49] See Daubrée's experiments on the mechanical effects of gas at high pressures, Comptes Rend. cxi., cxii. cxiii. and Bull. Soc. Geol. France, xix. (1891), p. 313.

cessive important eruption, a similar but minor operation takes place within the present cone. The hardened cake of lava forming the floor is burst open, and with it there usually disappears much of the upper part of the cone, and sometimes, as in 1872, a large segment of the crater-wall. The Valle del Bove on the eastern flank of Etna is a chasm probably due mainly to some gigantic prehistoric explosion.[50] The islands of Santorin (Figs. 65 and 66) bring before us evidence of a prehistoric catastrophe of a similar

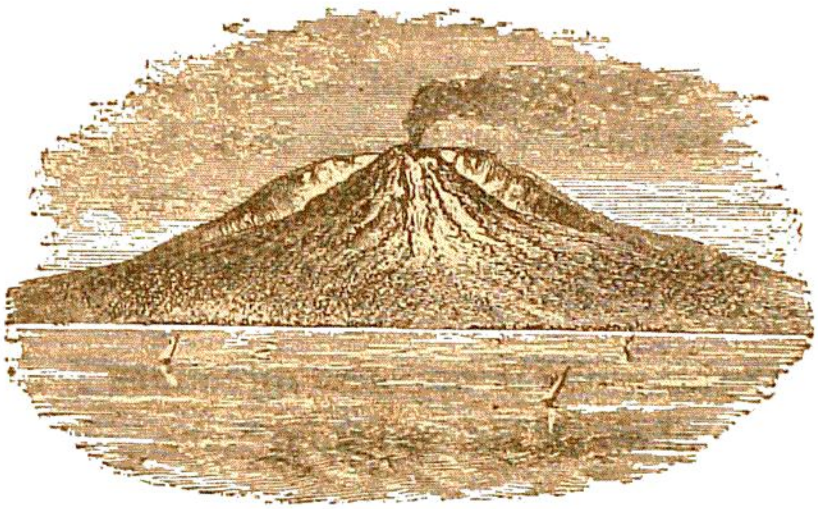

Fig. 45.—View of Vesuvius from the south, Showing the remaining part of the old crater-wall of Somma behind.

nature, by which a large volcanic cone was blown up. The existing outer islands are a chain of fragments of the periphery of the cone, the centre of which is now occupied by the sea. In the year 1538 a new volcano, Monte Nuovo, was formed in 24 hours on the margin of the Bay of Naples. An opening was drilled by successive explosions, and such quantities of stones, scoriæ, and ashes were thrown out from it as to form a hill that rose 440 English feet above the sea-level, and was more than a mile and a half in circumference. Most of the fragments now to be seen on the slopes of this cone and inside its beautifully perfect crater are of

[50] "Der Aetna," p. 400.

various volcanic rocks, many of them being black scoriæ; but pieces of Roman pottery, together with fragments of the older underlying tuff, and some marine shells, have been obtained—doubtless part of the soil and subsoil dislocated and ejected during the explosions.

One of the most stupendous volcanic explosions on record was that of Krakatoa in the Sunda Strait on the 26th and 27th of August, 1883.[51] After a series of convulsions, the greater portion of the island was blown out with a succession of terrific detonations which were heard more than 150 miles away. A mass of matter, estimated at about $1\frac{1}{8}$ cubic miles in bulk, was hurled into the air in the form of lapilli, ashes, and the finest volcanic dust. The effects of this volcanic outburst were marked both upon the atmosphere and the ocean. A series of barometrical disturbances passed round the globe in opposite directions from the volcano at the rate of about 700 miles an hour. The air-wave, travelling from east to west, is supposed to have passed three and a quarter times round the earth (or 82,200 miles) before it ceased to be perceptible.[52] The sea in the neighborhood was thrown into waves, one of which was computed to have risen more than 100 feet above tide-level, destroying towns, villages, and 36,380 people. Oscillations of the water were perceptible even at Aden, 1000 miles distant, at Port Elizabeth in South Africa, 5450 miles, and among the islands of the Pacific Ocean, and they are computed to have travelled with a maximum velocity of 467 statute miles in the hour.[53]

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[51] See "The Eruption of Krakatoa," by a Committee of the Royal Society, 1888. "Krakatau," R. D. M. Verbeck, Batavia, 1886.

[52] Scott and Strachey, Proc. Roy. Soc. xxxvi. (1883). Royal Society's Report, p. 57.

[53] Wharton, Royal Society's Report, p. 89. For a great Japanese explosion, see Nature, 13th Sept. 1888.

It is not necessary, and it does not always happen, that any actual solid or liquid volcanic rock is erupted by explosions that shatter the rocks through which the funnel passes. Thus, among the cones of the extinct volcanic tract of the Eifel, some occur which consist entirely, or nearly so, of comminuted débris of the surrounding Devonian graywacke and slate through which the various volcanic vents have been opened (see pp. 341, 417, 970). Evidently, in such cases, only elastic vapors forced their way to the surface; and we see what probably often takes place in the early stages of a volcano's history, though the fragments of the underlying disrupted rocks are in most instances buried and lost under the far more abundant subsequent volcanic materials. Sections of small ancient volcanic "necks" or pipes sometimes afford an excellent opportunity of observing that these orifices were originally opened by the blowing out of the solid crust and not by the formation of fissures. Examples will be cited in later pages from Scottish volcanic areas of Old Red Sandstone, Carboniferous, and Permian age. The orifices are there filled with fragmentary materials, wherein portions of the surrounding and underlying rocks form a noticeable proportion.[54] (See Figs. 296–301.)

Showers of Dust and Stones.—A communication having been opened, either by fissuring or explosion, between the heated interior and the surface, fragmentary materials are commonly ejected from it, consisting at first mainly of the rocks through which the orifice has been opened, afterward of volcanic substances. In a great eruption, vast numbers of red-hot stones are shot up into the air, and fall back partly into the crater and partly on the outer slopes of the

[54] Trans. Roy. Soc. Edin. xxix. p. 458; Quart. Journ. Geol. Soc. (1892), President's Address, pp. 86, 118, 135, 143, 153.

cone. According to Sir W. Hamilton, cinders were thrown by Vesuvius, during the eruption of 1779, to a height of 10,000 feet. Instances are known where large stones, ejected obliquely, have described huge parabolic curves in the air, and fallen at a great distance. Stones 8 lbs. in weight occur among the ashes which buried Pompeii. The volcano of Antuco in Chile is said to send stones flying to a distance of 36 (?) miles, Cotopaxi is reported to have hurled a 200-ton block 9 miles,[55] and the Japanese volcano, Asama, is said to have ejected many blocks of stone, measuring from 40 to more than 100 feet in diameter.[56]

But in many great eruptions, besides a constant shower of stones and scoriæ, a vast column of exceedingly fine dust rises out of the crater, sometimes to a height of several miles, and then spreads outward like a sheet of cloud. The remarkable fineness of this dust may be understood from the fact that during great volcanic explosions no boxes, watches, or close-fitting joints have been found to be able to exclude it. Mr. Whymper collected some dust that fell 65 miles away from Cotopaxi, and which was so fine that from 4,000 to 25,000 particles were required to weigh a grain.[57] So dense is the dust-cloud as to obscure the sun, and for days together the darkness of night may reign for miles around the volcano. In 1822, at Vesuvius, the ashes not only fell thickly on the villages round the base of the mountain, but travelled as far as Ascoli, which is 56 Italian miles distant from the volcano on one side, and as Casano, 105 miles on the other. The eruption of Cotopaxi, on 26th

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[55] D. Forbes, Geol. Mag. vii. p. 320.

[56] J. Milne, Seism. Soc. Japan, ix. p. 179, where an excellent account of the volcanoes of Japan is given. See also "The Volcanoes of Japan," by J. Milne and W. K. Burton.

[57] Royal Society Report on Krakatoa, p. 183.

June, 1877, began by an explosion that sent up a column of fine ashes to a prodigious height into the air, where it rapidly spread out and formed so dense a canopy as to throw the region below it into total darkness.[58] So quickly did it diffuse itself, that in an hour and a half, a previously bright morning became at Quito, 33 miles distant, a dim twilight, which in the afternoon passed into such darkness that the hand placed before the eye could not be seen. At Guayaquil, on the coast, 150 miles distant, the shower of ashes continued till the 1st of July. Dr. Wolf collected the ashes daily, and estimated that at that place there fell 315 kilogrammes on every square kilometre during the first thirty hours, and on the 30th of June, 209 kilogrammes in twelve hours.[59] During a much less important eruption of the same mountain on 3d July, 1880, the amount of volcanic dust ejected, according to Mr. Whymper, could not have been less, and was probably vastly more, than two millions of tons,[60] equivalent to a mass of lava containing more than 150,000 cubic feet.

The explosion of Krakatoa in August, 1883, was accompanied by the discharge of enormous quantities of volcanic dust, some of which was carried to vast distances. It was estimated that the clouds of fine dust were hurled from that volcano to a height of 17 miles, and the darkness which they caused extended for 150 miles from the focus of eruption. The diffusion and continued suspension of the finer particles

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[58] During the comparatively insignificant eruption of the volcano in 1880 Mr. Whymper noticed that a column of inky blackness, formed doubtless of volcanic dust, went straight up into the air with such velocity that in less than a minute it had risen 20,000 feet above the rim of the crater, or 40,000 feet above the sea. "Travels amongst the Great Andes," p. 322.

[59] Neues Jahrb. 1878, p. 141. An account of this eruption is given by Mr. Whymper in his "Travels amongst the Great Andes," chap. vi.

[60] "Travels amongst the Great Andes," p. 328.

of this dust in the upper air has been regarded as the probable cause of the remarkably brilliant sunsets of the following winter and spring over a large part of the earth's surface.[61] One of the most stupendous outpourings of volcanic ashes on record took place, after a quiescence of 26 years, from the volcano Coseguina, in Nicaragua, during the early part of the year 1835. On that occasion, utter darkness prevailed over a circle of 35 miles radius, the ashes falling so thickly that, even 8 leagues from the mountain, they covered the ground to a depth of about 10 feet. It was estimated that the rain of dust and sand fell over an area at least 270 geographical miles in diameter. Some of the finer materials, thrown so high as to come within the influence of an upper air-current, were borne away eastward, and fell, four days afterward, at Kingston, in Jamaica—a distance of 700 miles. During the great eruption of Sumbawa, in 1815, the dust and stones fell over an area of nearly one million square miles, and were estimated by Zollinger to amount to fully fifty cubic miles of material, and by Junghuhn to be equal to one hundred and eighty-five mountains like Vesuvius. Toward the end of the 18th century, during a time of great disturbance among the Japanese volcanoes, one of them, Sakurajima, threw out so much pumiceous material that it was possible to walk a distance of 23 miles upon the floating débris in the sea.

An inquiry into the origin of these showers of fragmentary materials brings vividly before us some of the essential features of volcanic action. We find that bombs, slags, and lapilli may be thrown up in comparatively tranquil states of a volcano, but that the showers of fine dust are discharged

[61] Royal Society Report, pp. 151–463.

with violence, and only appear when the volcano becomes more energetic. Thus, at the constantly, but quietly, active volcano of Stromboli, the column of lava in the pipe may be watched rising and falling with a slow rhythmical movement. At every rise, the surface of the lava swells up into blisters several feet in diameter, which by and by burst with a sharp explosion that makes the walls of the crater vibrate. A cloud of steam rushes out, carrying with it hundreds of fragments of the glowing lava, sometimes to a height of 1200 feet. It is by the ascent of steam through its mass, that a column of lava is kept boiling at the bottom of the crater, and by the explosion of successive larger bubbles of steam, that the various bombs, slags, and fragments of lava are torn off and tossed into the air. It has often been noticed at Vesuvius that each great concussion is accompanied by a huge ball-like cloud of steam which rushes up from the crater. Doubtless it is the sudden escape of that steam which causes the explosion.

The varying degree of liquidity or viscosity of the lava probably modifies the force of explosions, owing to the different amounts of resistance offered to the upward passage of the absorbed gases and vapors. Thus explosions and accompanying scoriæ are abundant at Vesuvius, where the lavas are comparatively viscid; they are almost unknown at Kilauea, where the lava is remarkably liquid.

In tranquil conditions of a volcano, the steam, whether collecting into larger or smaller vesicles, works its way upward through the substance of the molten lava, and as the elasticity of this compressed vapor overcomes the pressure of the overlying lava, it escapes at the surface, and there the lava is thus kept in ebullition. But this comparatively quiet operation, which may be watched within the craters of many active volcanoes, does not produce clouds of fine dust. The collision or friction of millions of stones ascending and descending in the dark column above the crater must doubtless cause much dust and sand. But the explosive action of steam is probably also an immediate cause of much trituration. The aqueous vapor or water-gas which is so largely dissolved in many lavas must exist within the lava-column, under an enormous pressure, at a temperature far above its critical point (p. 332), even at a white heat, and therefore possibly in a state of dissociation. The sudden ascent of lava so constituted relieves the pressure rapidly without sensibly affecting the temperature of the mass. Consequently, the white-hot gases or vapors at length explode, and reduce the molten mass to the finest powder, like water shot out of a gun.[62]

Evidently no part of the operations of a volcano has greater geological significance than the ejection of such enormous quantities of fragmentary matter. In the first place, the fall of these loose materials round the orifice of discharge is one main cause of the growth of the volcanic cone. The heavier fragments gather around the vent, and there too the thickest accumulation of dust and sand takes place. Hence, though successive explosions may blow out the upper part of the crater-walls and prevent the mountain from growing so rapidly in height, every eruption must increase the diameter of the cone. In the second place, as every shower of dust and sand adds to the height of the ground on which it falls, thick volcanic accumulations may

[62] Messrs. Murray and Renard (Proc. Roy. Soc. Edin. xii. (1884), p. 480) concluded that the fragmentary condition and the fresh fractures of the dust particles of the Krakatoa eruption were due to a tension phenomenon, which affects these vitreous matters in a manner analogous to what is observed in "Rupert's drops."

be formed far beyond the base of the mountain. The volcano of Sangay, in Ecuador, for instance, has buried the country around it to a depth of 4000 feet under its ashes.[63] In such loose deposits are entombed trees and other kinds of vegetation, together with the bodies of animals, as well as the works of man. In some cases, where the layer of volcanic dust is thin, it may merely add to the height of the soil, without sensibly interfering with the vegetation. But it has been observed at Santorin that though this is true in dry weather, the fall of rain with the dust at once acts detrimentally. On the 3d of June, 1866, the vines were there withered up, as if they had been burned, along the track of the smoke cloud.[64] By the gradual accumulation of volcanic ashes, new geological formations arise which, in their component materials, not only bear witness to the volcanic eruptions that produced them, but preserve a record of the land-surfaces over which they spread. In the third place, besides the distance to which the fragments may be hurled by volcanic explosions, or to which they may be diffused by the ordinary aerial movements, we have to take into account the vast spaces across which the finer dust is sometimes borne by upper air-currents. In the instance already cited, ashes from Coseguina fell 700 miles away, having been carried all that long distance by a high counter-current of air, moving apparently at the rate of about seven miles an hour in an opposite direction to that of the wind which blew at the surface. By the Sumbawa eruption, also referred to above, the sea west of Sumatra was covered with a layer of ashes two feet thick. On several occasions ashes from the Icelandic volcanoes have fallen so thickly between the Orkney

[63] D. Forbes, Geol. Mag. vii. 320.

[64] Fouqué, "Santorin," p. 81.

and Shetland Islands, that vessels passing there have had the unwonted deposit shovelled off their decks in the morning. In the year 1783, during the memorable eruption of Skaptar-Jökull, so vast an amount of fine dust was ejected that the atmosphere over Iceland continued loaded with it for months afterward. It fell in such quantities over parts of Caithness—a distance of 600 miles—as to destroy the crops; that year is still spoken of by the inhabitants as the year of "the ashie." Traces of the same deposit have been observed in Norway, and even as far as Holland.[65] Hence it is evident that volcanic accumulations may take place in regions many hundreds of miles distant from any active volcano. A single thin layer of volcanic detritus in a group of sedimentary strata would not thus of itself prove the existence of contemporaneous volcanic action in its neighborhood. Failing other proof of adjacent volcanic activity, it might have been wind-borne from a volcano in a distant region.

Lava-streams.—At its exit from the side of a volcano, lava glows with a white heat, and flows with a motion which has been compared to that of honey or of melted iron. It soon becomes red, and like a coal fallen from a hot fireplace, rapidly grows dull as it moves along, until it assumes a black, cindery aspect. At the same time the surface congeals, and soon becomes solid enough to support a heavy block of stone. The aspect of the stream varies with the composition and fluidity of the lava, form of the ground, angle of slope, and rapidity of flow. Viscous lavas, like those of Vesuvius, break up along the surface into rough

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[65] Nordenskiöld, Geol. Mag. 2d dec. iii. p. 292. G. vom Rath, Monatsber. K. Preuss. Akad. Wiss. 1876, p. 282. Neues Jahrb. 1876, p. 52, and postea, p. 575.

brown or black cinder-like slags and irregular ragged cakes, bristling with jagged points ("*aa*" [66]), which, in their onward motion, grind and grate against each other with a harsh metallic sound, sometimes rising into rugged mounds or becoming seamed with rents and gashes, at the bottom of which the red-hot glowing lava may be seen (Fig. 46). In lavas possessing somewhat greater fluidity, the surface presents froth-like, curving lines, as in the scum of a slowly

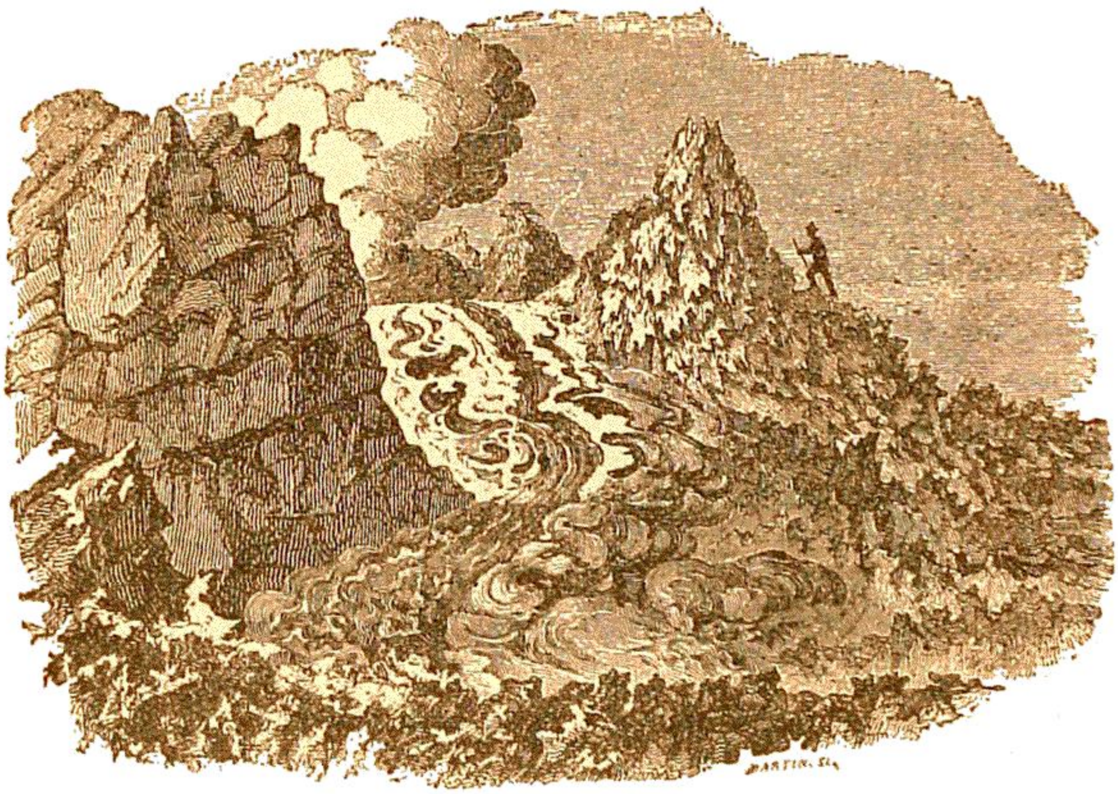

Fig. 46.—View of portion of a Lava-stream on Vesuvius (Abich).

flowing river, or is arranged in curious ropy folds, as the layers have successively flowed over each other and congealed ("*pahoehoe*" [66]). These, and many other fantastic coiled shapes were exhibited by the Vesuvian lava of 1858, and are admirably displayed by the peculiarly liquid glassy lavas of Kilauea.[66] Basalts possessing extreme liquidity

[66] For descriptions of Vesuvian lava-streams, see the various memoirs and works cited, ante, p. 333. For those of Etna, Sartorius von Waltershausen and A. von Lasaulx, "Der Aetna," ii. p. 390. The rugged scoriaceous lava-surfaces are known in Hawaii as *aa*, the smooth coiled and ropy surfaces are there called

have flowed for great distances with singularly smooth surfaces. A large area which has been flooded with lava is perhaps the most hideous and appalling scene of desolation anywhere to be found on the surface of the globe.

A lava-stream usually spreads out as it descends from its point of escape, and moves more slowly. Its sides look like huge embankments, or like some of the long mounds of

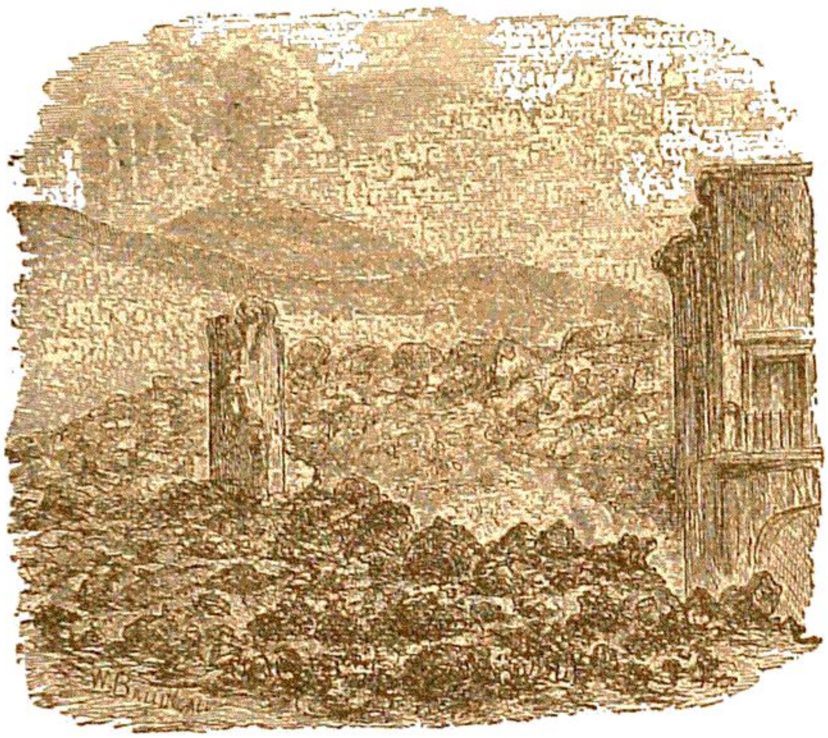

Fig. 47.—View of houses surrounded and partly demolished by the Lava of Vesuvius, 1872.

"clinkers" in a great manufacturing district. The advancing end is often much steeper, creeping onward like a great wall or rampart, down the face of which the rough blocks of hardened lava are ever rattling (Fig. 47).

Outflow of Lava.—This appears to be immediately due to the expansion of the absorbed vapors and gases in the molten rock. Though these vapors may reach the sur-

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pahoehoe. Dana, "Characteristics of Volcanoes," p. 9. The same stream of lava may exhibit both these aspects in different parts of its course. Ibid. p. 209 and Mr. Johnston-Lavis' papers on Vesuvius, already cited p. 333.

face, and even produce tremendous explosions, without an actual outcome of lava, yet so intimately are vapors and lava commingled in the subterranean reservoirs, that they commonly rise together, and the explosions of the one lead to the outflow of the other. The first point at which the lava makes its appearance at the surface will largely depend upon the structure of the ground. Two causes have been assigned on a foregoing page (p. 356) for the fissuring of a volcanic cone. As the molten mass rises within the chimney of the volcano, continued explosions of vapor take place from its upper surface. The violence of these may be inferred from the vast clouds of steam, ashes, and stones hurled to so great a height into the air, and from the concussions of the ground, which may be felt at distances of more than 100 miles from the volcano. It need not be a matter of surprise, therefore, that the sides of a great vent, exposed to shocks of such intensity, should at last give way, and that large divergent fissures should be opened down the cone. Again, the hydrostatic pressure of the column of lava must, at a depth of 1000 feet below the top of the column, exert a pressure of between 70 and 80 tons on each square foot of the surrounding walls (p. 356). We may well believe that such a force, acting upon the walls of a funnel already shattered by a succession of terrific explosions, may prove too great for their resistance. When this happens, the lava pours forth from the outside of the cone. On a much-fissured cone, lava may issue freely from many points, so that a volcano so affected has been graphically described as "sweating fire."

In a lofty volcano, lava occasionally rises to the lip of the crater and flows out there; but more frequently it escapes from some fissure or orifice in a weak part of the cone. In minor volcanoes, on the other hand, where the explosions are less violent, and where the thickness of the cone in proportion to the diameter of the funnel is often greater, the lava very commonly rises into the crater. Should the crater-walls be too weak to resist the pressure of the molten mass, they give way, and the lava rushes out from the breach. This is seen to have happened in several of the puys of Auvergne, so well figured and described by Scrope (Fig. 48).[67] But if the crater be massive

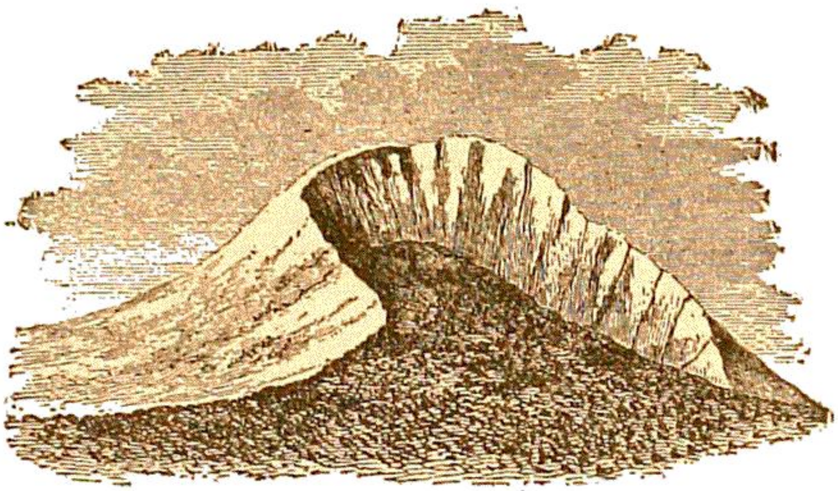

Fig. 48.—View of one of the Tuff-cones of Auvergne, broken down on one side by the escape of a stream of Lava. (After Scrope.)

enough to withstand the pressure, the lava may at last flow out from the lowest part of the rim.

In a tall column of molten lava, there may be a variation in the density of its different parts, the heaviest naturally gravitating to the bottom. It has been observed by Ch. Vélain that at the Isle of Bourbon (Réunion), the lavas escaping from the base of the volcanic cone are denser

[67] For descriptions of this region, see Scrope's "Geology and Extinct Volcanoes of Central France," 2d edit. 1858. H. Lecoq's "Epoques géologiques de l'Auvergne," 1867. Michel-Lévy, Bull. Soc. Geol. France, xviii. (1890), p. 688. The succession of volcanic rocks in Velay is described by M. Boule, Bull. Soc. Geol. France, xviii. (1889), p. 174, and in Bull. Carte Geol. de la France, No. 28 (1892); see also op. cit. No. 13 for a memoir by P. Termier.

and more basic than those which flow out from the lip of the crater.[68]

As soon as the molten rock reaches the surface, the superheated water-vapor or gas, dissolved within its mass, escapes copiously, and hangs as a dense white cloud over the moving current. The lava-streams of Vesuvius sometimes appear with as dense a steam-cloud at their lower ends as that which escapes at the same time from the main crater. Even after the molten mass has flowed several miles, steam continues to rise abundantly both from its end and from numerous points along its surface, and continues to do so for many weeks, months, or it may be for several years.

Should the point of escape of a lava-stream lie well down on the cone, far below the summit of the lava-column in the funnel, the molten rock, on its first escape, driven by hydrostatic pressure, will sometimes spout up high into the air—a fountain of molten rock. This was observed in 1794 on Vesuvius, and in 1832 on Etna. In the eruption of 1852 at Mauna Loa, an unbroken fountain of lava, from 200 to 700 feet in height and 1000 feet broad, burst out at the base of the cone. Similar "geysers" of molten rock have subsequently been noticed in the same region. Thus in March and April, 1868, four fiery fountains, throwing lava to heights varying from 500 to 1000 feet, continued to play for several weeks. According to Mr. Coan, such outbursts take place from the bottom of a column of lava 3000 feet high. The volcano of Mauna Loa strikingly illustrates another feature of volcanic dynamics in the position and outflow of lava. It bears upon its flanks at a distance

[68] "Les Volcans," p. 36. For references relating to this island, see p. 415.

of 20 miles, but 10,000 feet lower, the huge crater Kilauea. As Dana has pointed out, these orifices form part of one mountain, yet the column of lava stands 10,000 feet higher in one conduit than in the other. On a far smaller scale the same independence occurs among the several pipes of some of the geysers in the Yellowstone region of North America.

From the wide extent of basalt-dikes, such as those of Tertiary age in Britain, which rise to the surface at a distance of 200 miles from the main remnants of the volcanic outbursts of their time, and are found over an area of perhaps 100,000 square miles, it is evident that molten lava may sometimes occupy a far greater space within the crust than might be inferred from the dimensions and outpourings even of the largest volcanic cone. There can be no doubt that vast reservoirs of melted rock, impregnated with superheated vapors, must formerly have existed, if they do not exist still, beneath extensive tracts of country (p. 967). Yet even in these more stupendous manifestations of volcanism, the lava should be regarded rather as the sign than as the cause of volcanic action. The cause of the ascent of the lava in volcanic pipes is still obscure: it may possibly be due to the compression arising from the secular contraction of the earth. But it is doubtless the pressure of the imprisoned vapor, and its struggles to get free, which produce the subterranean earthquakes and the explosions from the vents. As soon as the vapor finds relief, the terrestrial commotion calms down again, until another accumulation of vapor demands a repetition of the same phenomena.

Rate of flow of Lava.—The rate of movement is regulated by the fluidity of the lava, by its volume, and by the form and inclination of the ground. Hence, as a rule, a lava-stream moves faster at first than afterward, because it has not had time to stiffen, and its slope of descent is usually steeper than further down the mountain. One of the most fluid and swiftly flowing lava-streams ever observed on Vesuvius was that erupted on 12th August, 1805. It is said to have rushed down a space of 3 Italian ($3\frac{3}{8}$ English) miles in the first four minutes, but to have widened out and moved more slowly as it descended, yet finally to have reached Torre del Greco in three hours. A lava erupted by Mauna Loa in 1852 went as fast as an ordinary stage-coach, or fifteen miles in two hours; but some of the lavas from that mountain have in parts of their course moved with double that rapidity. Long after a current has been deeply crusted over with slags and rough slabs of lava, it may continue to creep slowly forward for weeks or even months.

It happens sometimes that, as the lava moves along, the still molten mass inside bursts through the outer hardened and deeply seamed crust, and rushes out with, at first, a motion much more rapid than that of the main stream. Any sudden change in the form or slope of the ground affects the flow of the lava. Thus, reaching the edge of a steep defile or cliff, the molten rock pours over in a cataract of glowing, molten rock, with clouds of steam, showers of fragments, and a noise utterly indescribable. Or, on the other hand, encountering a ridge or hill across its path, it accumulates until it either finds egress round the side or actually overrides and entombs the obstacle. The hardened crust or shell, within which the still fluid lava moves, serves to keep the mass from spreading. Here and there, inside this crust, the lava subsides, leaving cavernous spaces and tunnels into which, when the whole is cold, one may creep, and which are sometimes festooned with stalactites of lava (p. 387).

Size of Lava-streams.—In some cases, lava escaping from craters or fissures comes to rest before reaching the base of the slopes, like the obsidian current which has congealed on the side of the little volcanic island of Volcano.[69] In other instances, the molten rock not only reaches the plains but flows for many miles away from the point of eruption. Sartorius von Waltershausen computed the lava emitted by Etna in 1865 at 92 millions of cubic metres, that of 1852 at 420 millions, that of 1669 at 980 millions, and that of a prehistoric lava-stream near Randazzo at more than 1000 millions.[70] The most stupendous outpouring of lava on record was that which took place in Iceland in the year 1783. Successive streams issued from a fissure about 12 miles long, filling up river-gorges which were sometimes 600 feet deep and 200 feet broad, and advancing into the alluvial plains in lakes of molten rock 12 to 15 miles wide and 100 feet deep. Two currents of lava which, filling up the valley of the Skapta, escaped in nearly opposite directions, extended for 45 and 50 miles respectively, their usual thickness being 100 feet. Bischof estimated that the total amount of lava poured forth during this single eruption "surpassed in magnitude the bulk of Mont Blanc."[71]

Varying liquidity of Lava.—All lava, at the time of its expulsion, is in a molten condition. It usually

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[69] Recent eruptions in this island have consisted entirely of ashes. A. Baltzer, Zeitsch. Deutsch. Geol. Ges. xxvi. (1875), p. 36. G. Mercalli, "Le Eruzioni dell' Isola Vulcano," Rassegna Nazionale, 1889; also a paper by same author in Atti. Soc. Ital. Sci. Nat., vol. xxxi.

[70] "Der Aetna," ii. 303.

[71] Lyell, "Principles," ii. p. 49. Helland, "Lakis Kratere," cited ante, p. 345.

consists of a glassy magma in which, by reason of the high temperature, most or even all of the mineral constituents exist dissolved. Considerable differences, however, have been observed in the degree of liquidity. Humboldt and Scrope long ago called attention to the thick, short, lumpy forms presented by masses of solidified trachytic rocks, which are lighter and more siliceous, and to the thin, widely extended sheets assumed by basalts, which are heavy and contain much iron and basic silicates.[72] It may be inferred that, as a rule, the basalts or basic lavas have been more liquid than the trachytes or siliceous lavas. The cause of this difference has been variously explained. It may depend partly upon chemical composition, the siliceous being naturally less fusible than the basic rocks. But as great differences of fluidity are observable even among lavas having nearly the same composition, there would seem to be some further cause for the diversity. Reyer has ingeniously maintained that we must look to original differences in the extent to which the subterranean igneous magma that supplied the lava has been saturated with vapors and gases. Molten rock highly impregnated gives rise, he holds, to fragmentary discharges, while when feebly impregnated it flows out tranquilly.[73] On the other hand, Captain C. E. Dutton, who has studied the volcanic phenomena of Western America and Hawaii, suggests that the different degrees of liquidity may depend not only on chemical differences, but on variations of temperature. He supposes that the basaltic lavas which have spread so far in thin sheets, and which must have had a comparatively great liquidity, flowed at temperatures far

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[72] Scrope, "Considerations on Volcanoes" (1825), p. 93.
[73] "Beitrag zur Physik der Eruptionen," p 77.

above that of their melting-point, and were, to use his phrase, "superfused."[74]

The varying degrees of liquidity are manifested in a characteristic way on the surface of lava. Thus, in the great lava-pools of Hawaii, the rock exhibits a remarkable liquidity, throwing up fountains of molten rock to a height of 300 feet or more. During its ebullition in the crater-pools, jets and dribblets, a quarter of an inch in diameter, are tossed up, and falling back on one another, make "a column of hardened tears of lava," one of which (Fig. 49) was found to have attained a height of 40 feet, while in other places the jets thrown up and blown aside by the wind give rise to long threads of glass which lie thickly together like mown grass, and are known by the natives under the name of "Pele's Hair," after one of their divinities.[75] Yet although the ebullition is caused by the uprise and escape of highly heated vapors, there is no cloud over the boiling lake itself, heavy white vapor only escaping at different points along the edge.

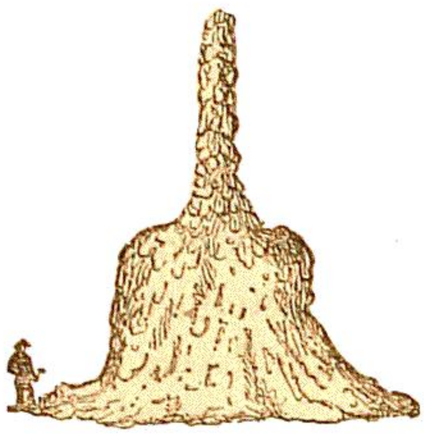

Fig. 49.—Column formed of congealed jets of liquid Lava, Crater of Kilauea (Dana).

On the other hand, the lavas of Vesuvius and of most modern volcanoes, which issue so saturated with vapor as to be nearly concealed from view in a cloud of steam, are accompanied by abundant explosions of fragmentary materials. Slags and clinkers, torn by explosions of steam from the

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[74] "High Plateaus of Utah," Geog. and Geol. Sur. Territories. Washington, 1880, chap. v.

[75] Dana, Geol. U. S. Explor. Exped., "Geology," p. 179; "Characteristics of Volcanoes," p. 160.

molten rock, are strewn abundantly over the cone, while the surface of the lava is likewise rugged with similar clinkers, which may now and then be observed piled up round some more energetic steam-spiracle. Sometimes the vapor forces up the lava round such a spiracle or fumarole and gradually piles up a rugged column several feet or yards in height, as

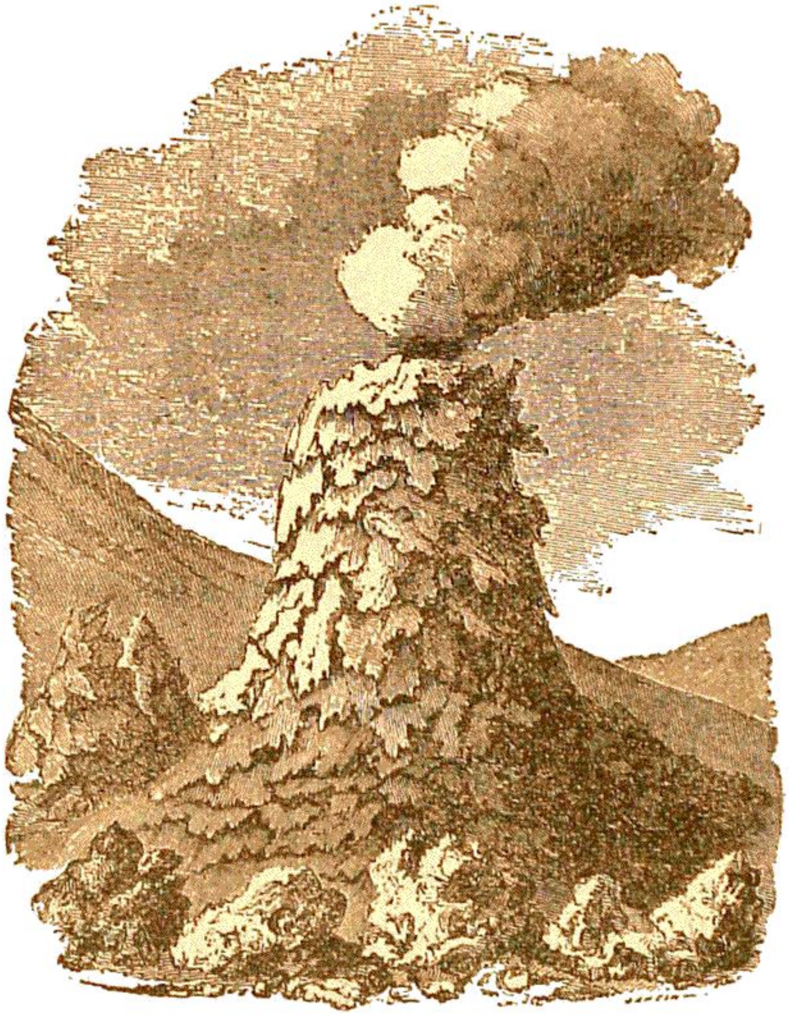

Fig. 50.—Lava-column (eight feet high), Vesuvius (Abich).

has been observed on Vesuvius[76] (Figs. 46, 49, 50). So vast an amount of steam rushes out from one of these orifices, and with such boiling and explosion, that the cone of bombs, slags, and irregular lumps of lava forms a miniature or parasitic volcano, which will remain as a marked cone on its

[76] Some good examples were observed on this mountain in the summer of 1891 by Mr. Johnston-Lavis, Brit. Assoc. 1891, sect. C.

parent mountain long after the eruption which gave it birth has ceased. The lava of the eruption at Santorin in 1866–67 at first welled out tranquilly, but after a few days its outflow was accompanied by explosions and discharges of incandescent fragments, which increased until they had covered the lava dome with ejected scoriæ, and had opened a number of crateriform mouths on its summit.[77]

There can be no doubt, as above remarked, that the condition of liquidity of the lava has in some measure determined the form of the eruptions. In one case, there are quiet outwellings of the more liquid lavas, as at Hawaii; in another, there are explosive discharges and cinder-cones, accompanying the more viscid lavas, as at most modern volcanoes. The former has been the condition favorable to the most colossal outpourings of molten rock, as we see in the basalt-plateaus of Britain, Faroe, Greenland, Idaho, and Oregon, the Ghauts, Abyssinia, etc. This subject is again referred to at p. 433.

Crystallization of Lava.—Pouring forth with a liquidity like that of molten iron, lava speedily assumes a more viscous condition and a slower motion. Obsidian and other vitreous rocks have consolidated as glass: yet that they are not always extremely fluid is indicated by the arrest of the obsidian stream half-way down the steep northern slope of Volcano. Even in such perfect natural glass as obsidian, microscopic crystallites and crystals are usually present, and in prodigious numbers (pp. 205, 282). In most lavas, devitrification has proceeded so far before the final stiffening, that the original glassy magma has passed into a more or less completely lithoid or crystalline mass.

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[77] Fouqué, "Santorin," p. xv.

That lava may possess an appreciably crystalline structure while still in motion, has often been proved at Vesuvius, where well-defined crystals of the infusible leucite may be observed in a molten magma of the other minerals, portions of the white-hot rock in this condition being ladled out, impressed with a stamp and suddenly congealed. The fluxion-structure above described (pp. 178, 213) furnishes interesting evidence of this fact in many ancient as well as modern lavas.

There is reason to believe that in the molten magma beneath a volcano considerable progress may be made in the development of some crystalline minerals out of the surrounding glass, and that this crystalline portion may be to some extent separated from the vitreous residue. Hence where this has taken place, subsequent eruptions may give rise to a more crystalline and probably more basic lava from one point of emission and a more glassy and probably more acid lava from another vent. Or we may conceive that the two portions of the magma may be subsequently mingled again in various proportions before eruption.[78] If the process of differentiation should continue, as seems natural, during the lapse of a whole cycle of a volcano's history, the earlier lavas would be more basic than the later.

The crystalline structure of lava has been supposed to be in some measure determined by the presence of the volcanic vapors and gases with which the molten rock is impregnated, the rapid escape of these vapors preventing the formation of the crystalline structure, and leaving the lava in the condition of a more or less perfect glass. But the experiments of

[78] Compare the observation of Ch. Vélain cited ante, p. 219, and the remarks postea, pp. 444, 457, 936. Consult on this subject a paper by Prof. Judd, Geol. Mag. 1888, p. 1.

MM. Fouqué and Michel-Lévy (postea, p. 513) have shown that rocks, having in every essential particular the characters of volcanic lavas, may be artificially produced under ordinary atmospheric pressure by simple dry fusion. There appears to be no doubt that the presence of water lowers the fusion-point of silicates, though what precise influence the dissolved vapors exert upon the ultimate consolidation of molten lava has yet to be ascertained. Difference in the rate of cooling has doubtless been an important, if not the main, factor in determining the various conditions of texture of lava-streams. The crystalline structure may be expected to be most perfect where, as within thick masses of rock, the cooling has been prolonged, and where, consequently, the crystals have had ample time and opportunity for their formation. On the other hand, the glassy structure will naturally be most perfectly shown where the cooling has been most rapid, as in the vitreous crust on the walls of dikes already referred to (pp. 297, 358). Rocks crystallizing in the deeper parts of a volcano usually possess a more coarsely crystalline structure than those which crystallize at or near to the surface (p. 936).

Temperature of Lava.—It would be of the highest interest and importance to know accurately the temperature at which a lava-stream first issues. Measurements not altogether satisfactory have been taken at various distances below the point of emission, where the moving lava could be safely approached. Experiments made at Vesuvius by Scacchi and Sainte-Claire Deville in 1855, by thrusting thin wires of silver, iron, and copper into the lava, indicated a temperature of scarcely 700° C. (1228° Fahr.). Observations of a similar kind, made in 1819, when a silver wire $\frac{1}{80}$th inch in diameter at once melted in the Vesuvian lava of that year, gave a greatly higher temperature, the melting-point of silver being about 1800° Fahr. But copper wire has also been melted, the point of fusion of this metal being about 2204° Fahr. Evidence of the high temperature of lava has likewise been adduced from the alteration it has effected upon refractory substances in its progress, as where, at Torre del Greco, it overflowed the houses, and was afterward found to have fused the fine edges of flints, to have decomposed brass into its component metals, the copper actually crystallizing, and to have melted silver, and even sublimed it into small octahedral crystals (p. 393). The lava of Santorin has caught up pieces of limestone, and has formed out of them nodules containing crystallized anorthite, augite, sphene, black garnet, and particularly wollastonite.[79] The initial temperature of lava, as it first issues from the Vesuvian funnel, is probably considerably more than 2000° Fahr. Obviously the dissolved water (or water-substance, for, as already remarked, the temperature is far above the critical point of water, and its component gases may exist dissociated) must possess as high a temperature as that of the white-hot lava in which it is contained. The existence of the elements of water at a white heat, even in rocks which have reached the surface, is a fact of no little significance in the theoretical consideration of hypogene action.

Inclination and thickness of lava-flows.—It was at one time supposed that lava could not consolidate in beds on such steep slopes as those of most volcanoes. Hence arose the "elevation-crater theory" (described at p. 412), in which the inclined position of lavas round a volcanic vent was explained by upheaval after their

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[79] Fouqué, "Santorin," p. 206.

emission. Observations all over the world, however, have now demonstrated that lava, with all its characteristic features, can consolidate on slopes of even 35° and 40°.[80] The lava in the Hawaii Islands has cooled rapidly on slopes of 25°, that from Vesuvius, in 1855, is here and there as steep as 30°, while the older lavas in Monte Somma are sometimes inclined at 45°. On the east side of Etna, a cascade of lava, which in 1689 poured into the vast hollow of the Cava Grande, has an inclination varying from 18° to 48°, with an average thickness of 16 feet. On Mauna Loa some lava-flows are said to have congealed on slopes of 49°, 60°, and even 90°,[81] though in these cases it could only be a layer of rock, stiffening and adhering to the surface of the declivity. On the other hand, lava-streams have travelled considerable distances over ground that to the eye looks quite level. Among the Hawaiian Islands a declivity of 1° or less has been quite sufficient for the flow of the extremely liquid and mobile lavas of that region. In the great lava-fields of the Snake River region of the Western Territories of the United States the basalts, which must also have been extremely liquid, have flowed over slopes of much less than 1°.[82] The breadth and length of a lava-stream, as well as the form of its surface, depend mainly upon the liquidity of the molten material at the time of outflow. Even when it consolidates on a steep slope, a stream of lava forms a sheet with parallel upper and under surfaces, a general uniformity of thickness, and often greater evenness of surface, than where the angle of descent is low. The thickness varies indefinitely; many basalts which have

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[80] Lyell on the consolidation of lava on steep slopes, Phil. Trans. 1858.
[81] J. D. Dana, Amer. Jour. Sci. xxxv. (1888), p. 32.
[82] J. D. Dana, "Characteristics of Volcanoes," p. 12.

been poured out in a remarkably liquid condition have solidified in beds not more than 10 or 12 feet thick. On the other hand, more pasty lavas, and lavas which have flowed into narrow valleys, may be piled up in solid masses to a thickness of several hundred feet (pp. 378, 391).

Structure of a lava-stream.—Lava-streams are sometimes nearly homogeneous throughout. In general, however, they each show three component layers. At the bottom lies a rough, slaggy mass, produced by the rapid cooling of the lava, and the breaking up and continued onward motion of the scoriform layer. The central and main portion of the stream consists of solid lava, often, however, with a more or less carious and vesicular texture. The upper part, as we have seen, may be a mass of rough broken-up slabs, scoriæ, or clinkers. The proportions borne by these respective layers to each other vary continually. Some of the more fluid ropy lavas of Vesuvius have an inconstant and thin slaggy crust; others may be said to consist of little else than scoriæ from top to bottom. Throughout the whole mass of a lava-current, but more especially along its upper surface, the absorbed or dissolved water-vapor expands with diminution of pressure, and pushing the molten rock aside, segregates into small bubbles or irregular cavities. Hence, when the lava solidifies, these steam-holes are seen to be sometimes so abundant that a detached portion of the rock containing them will float in water (pumice). They are often elongated in the direction of the motion of the lava-stream (Fig. 51). Some-

Fig. 51.—Elongation of vesicles in direction of flow of lava.

times, indeed, where the cells are numerous, their elongation in one direction gives a fissile structure to the rock.

A singular feature in many lava-streams are the tunnels and caverns already referred to (p. 377) as observable in them. These cavities have doubtless arisen during the flow of the mass when the upper and under portions had solidified and were creeping sluggishly onward, while the still molten interior was able to move faster and thus to leave empty spaces behind it. Such tunnels may frequently be seen among the Vesuvian lava-streams. Some remarkable examples are described from the highly glassy lavas of Hawaii, where they are sometimes from 2 to 10 feet in height and 30 feet broad, but with large lateral expansions. The walls of these Hawaiian lava-chambers are smooth and even glassy, and from their roofs hang slender stalactites of lava 20 to 30 inches long, while on the floor below little mounds of lava-stalagmite have formed. The precise mode of origin of these curious appendages is not yet understood.[83]

In passing from a fluid to a solid condition, and thus contracting, lava acquires different structures. Lines of divisional planes or joints traverse it, especially perpendicular to the upper and under surfaces of the sheet. These sometimes assume prismatic forms, dividing the rock into columns, as is so frequently to be observed in basalt. They are described in Book IV. Part II., together with other forms of joints.

V a p o r s a n d s u b l i m a t i o n s o f a l a v a - s t r e a m. —Besides steam, many other vapors, absorbed in the original subterranean molten magma, escape from the fissures of a lava-stream. Such vapors are copiously disengaged at

[83] See Dana's "Characteristics of Volcanoes," pp. 209, 332.

fumaroles (pp. 332, 334). Among the exhalations, chlorides abound, particularly chloride of sodium, which appears, not only in fissures, but even over the cooled crust of the lava, in small crystals, in tufts, or as a granular and even glassy incrustation. Chloride of iron is deposited as a yellow coating at fumaroles, where also bright emerald-green films and scales of chloride of copper may be more rarely observed. Many chemical changes take place in the escape of these vapors. Thus specular-iron, either the result of the mutual decomposition of steam and iron-chloride, or of the oxidation of magnetite, forms abundant scales, plates, and small crystals in the fumaroles and vesicles of some lavas. Sal-ammoniac also appears in large quantity on many lavas, not merely in the fissures, but also on the upper surface. In these cases, it is not directly a volcanic product, but results from some decomposition, possibly from the gases evolved by the sudden destruction of vegetation. It has, however, been observed also in the crater of Etna, where the co-operation of organic substance is hardly conceivable, and where perhaps it may arise from the decomposition of aqueous vapor, whereby a combination is formed with atmospheric nitrogen. Sulphur, breislakite, szaboite, tenorite, alum, sulphates of iron, soda and potash, and other minerals are also found.

Slow cooling of lava.—The hardened crust of a lava-stream is a bad conductor of heat. Consequently, the surface of the stream may have become cool enough to be walked upon, though the red-hot mass may be observed through the rents to lie only a few inches below. Many years, therefore, may elapse before the temperature of the whole mass has fallen to that of the surrounding soil. Eleven months after an eruption of Etna, Spallanzani could see that the lava was still red-hot at the bottom of the fissures, and a stick thrust into one of them instantly took fire. The Vesuvian lava of 1785 was found by Breislak, seven years afterward, to be still hot and steaming internally, though lichens had already taken root on its surface. The ropy lava erupted by Vesuvius in 1858 was observed by the author in 1870 to be still so hot, even near its termination, that steam issued abundantly from its rents, many of which were too warm to allow the hand to be held in them, and three years later it was still steaming abundantly. Hoffmann records that from the lava which flowed from Etna in 1787, steam was still issuing in 1830. Yet more remarkable is the case of Jorullo, in Mexico, which sent out lava in 1759. Twenty-one years later a cigar could be lighted at its fissures; after 44 years it was still visibly steaming; and even in 1846, that is, after 87 years of cooling, two vapor-columns were still rising from it.[84]

This extremely slow rate of cooling has justly been regarded as a point of high geological significance, in regard to the secular cooling and probable internal temperature of our globe. Some geologists have argued, indeed, that if so comparatively small a portion of molten matter as a lava-stream can maintain a high temperature under a thin, cold crust for so many years, we may, from analogy, feel little hesitation in believing that the enormously vaster mass of the globe may, beneath a relatively thin crust, still continue in a molten condition within. More legitimate deductions, however, might be drawn from more accurate and precise measurements of the rate of loss of heat, and of its variations in different lava-streams. Lord Kelvin, for instance,

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[84] E. Schleiden, quoted by Naumann, "Geognosie," i. p. 160.

has suggested that, by measuring the temperature of intrusive masses of igneous rock in coal-workings and elsewhere, and comparing it with that of other non-volcanic rocks in the same regions, we might obtain data for calculating the time which has elapsed since these igneous sheets were erupted (*ante*, p. 94).

Effects of lava-streams on superficial waters and topography.—In its descent, a stream of lava may reach a water-course, and, by throwing itself as an embankment across the stream, may pond back the water and form a lake. Such is the origin of the picturesque Lake Aidat in Auvergne. Or the molten current may usurp the channel of the stream, and completely bury the whole valley, as has happened again and again among the vast lava-fields of Iceland. Few changes in physiography are so rapid and so enduring as this. The channel which has required, doubtless, many thousands of years for the water laboriously to excavate, is sealed up in a few hours under 100 feet or more of stone, and another vastly protracted interval may elapse before this newer pile is similarly eroded.[85]

By suddenly overflowing a brook or pool of water, molten lava sometimes has its outer crust shattered to fragments by a sharp explosion of the generated steam, while the fluid mass within rushes out on all sides.[86] The lava emitted by Mauna Loa, Hawaii, in the spring of 1868 flowed out to sea, and added half a mile to the extent of

[85] For an example of the conversion of a lava-buried river-bed into a hill-top by long-continued denudation, see Quart. Journ. Geol. Soc. 1871, p. 303.

[86] Explosions of this nature have been observed on Etna, where the lava has suddenly come in contact with water or snow, considerable loss of life being sometimes the result. Sartorius von Waltershausen and A. von Lasaulx, "Der Aetna," i. pp. 295, 300.

the island at that point. At the end of the stream three cinder-cones formed from the contact of the lava with the water, and Captain Dutton calls special attention to the fact that not only in this instance, but in other examples among the Hawaiian lavas which have reached the sea, there is clear evidence of the formation of ordinary volcanic craters by the accidental contact of lava with water.[67] The lavas of Etna and Vesuvius have also protruded into the sea, but, owing probably to their more viscous and lithoid condition and lower temperature, they do not seem to have given rise to explosive action at their seaward ends. Thus a current from the latter mountain entered the Mediterranean at Torre del Greco in 1794, and pushed its way for 360 feet outward, with a breadth of 1100 and a height of 15 feet. So quietly did it advance, that Breislak could sail round it in a boat and observe its progress.

By the outpouring of lava, two important kinds of geological change are produced. (1) Stream-courses, lakes, ravines, valleys, in short, all the minor features of a landscape, may be completely overwhelmed under a thick sheet of lava. The drainage of the district being thus effectually altered, the numerous changes which flow from the operations of running water over the land are arrested and made to begin again in new channels. (2) Considerable alterations may likewise be caused by the effects of the heat and vapors of the lava upon the subjacent or contiguous ground. Instances have been observed in which the lava has actually melted down opposing rocks, or masses of slags on its own surface. Interesting observations, already referred to (p. 385), have been made at Torre del Greco under the lava-

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[67] U. S. Geol. Report for 1882–83, p. 181.

stream which overflowed part of that town in 1794. It was found that the window-panes of the houses had been devitrified into a white, translucent, stony substance; that pieces of limestone had acquired an open, sandy, granular texture, without loss of carbon-dioxide, and that iron, brass, lead, copper, and silver objects had been greatly altered, some of the metals being actually sublimed. We can understand, therefore, that, retaining its heat for so long a time, a mass of lava may induce many crystalline structures, rearrangements, or decompositions in the rocks over which it comes to rest, and proceeds slowly to cool. This is a question of considerable importance in relation to the behavior of ancient lavas which, after having been intruded among rocks beneath the surface, have subsequently been exposed by denudation (Book IV. Part VII.).

But, on the other hand, the exceedingly trifling change produced, even by a massive sheet of lava, has often been remarked with astonishment. On the flank of Vesuvius, vines and trees may be seen still flourishing on little islets of the older land-surface, completely surrounded by a flood of lava. Dana has given an instructive account of the descent of a lava-stream from Kilauea in June, 1840. Islet-like spaces of forest were left in the midst of the lava, many of the trees being still alive. Where the lava flowed round the trees, the stumps were usually consumed, and cylindrical holes or casts remained in the lava, either empty or filled with charcoal. In many cases, the fallen crown of the tree lay near, and so little damaged that the epiphytic plants on it began to grow again. Yet so fluid was the lava that it hung in pendent stalactites from the branches, which nevertheless, though clasped round by the molten rock, had barely their bark scorched. Again, for nearly 100 years there has lain on the flank of Etna a large sheet of ice, which, originally in the form of a thick mass of snow, was overflowed by lava, and has thereby been protected from the evaporation and thaw which would certainly have dissipated it long ago, had it been exposed to the air. The heat of the lava has not sufficed to melt it. Extensive tracts of snow were likewise overspread by lava from the same mountain in 1879. In other cases, snow and ice have been melted in large quantities by overflowing lava. The great floods of water which rushed down the flank of Etna, after an eruption of the mountain in the spring of 1755, and similar deluges at Cotopaxi, are thus explained.

One further aspect of a lava-stream may be noticed here —the effect of time upon its surface. While all kinds of lava must, in the end, crumble down under the influence of atmospheric waste and, where other conditions permit, become coated with soil, and support some kind of vegetation, yet extraordinary differences may be observed in the facility with which different lava-streams yield to this change, even on the flank of the same mountain. Every one who ascends the slopes of Vesuvius remarks this fact. After a little practice, it is not difficult there to trace the limits of certain lavas even from a distance, in some cases by their verdure, in others by their barrenness. Five hundred years have not sufficed to clothe with green the still naked surface of the Catanian lava of 1381; while some of the lavas of the present century have long given footing to bushes of furze.[88] Some of the younger lavas of Auvergne, which certainly flowed in times anterior to those of history, are still singularly bare and rugged. Yet, on the whole,

[88] On the weathering of the Etna lavas, see "Der Aetna," ii. p. 397.

where lava is directly exposed to the atmosphere, without receiving protection from occasional showers of volcanic ash, or where liable to be washed bare by heavy torrents of rain, its surface decays in a few years sufficiently to afford soil for stray plants in the crevices. When these have taken root they help to increase the disintegration; at last, as the rock is overspread, the traces of its volcanic origin fade away from its surface. Some of the Vesuvian lavas of the present century already support vineyards.

Elevation and Subsidence.—Proofs of elevation are frequent among volcanic vents which, lying near the sea and containing marine sediments among their older erupted materials, supply, in the inclosed marine organisms, evidence of the movement. In this way, it is known that Etna, Vesuvius, and other Mediterranean volcanoes, began their history as submarine vents, and that they owe their present dimensions not only to the accumulation of ejected materials, but also, to some extent, to an elevation of the sea-bottom.

Proof of subsidence is less easily traced, but indications have been observed of a sinking of the ground beneath a volcanic vent. During the eruption of Santorin in 1866–67, very decided but extremely local subsidence took place near the vent in the centre of the old crater. The discharge of such prodigious quantities of material may tend to produce cavernous spaces in the terrestrial crust, and the weight of the ejected lavas and tuffs may still further contribute to a general settlement of the ground around a volcanic focus.

If we consider the records of volcanic action in past geological time we meet with many proofs that it took place in areas where the predominant terrestrial movement was one of subsidence. Thus among the Palæozoic systems of Britain, the Cambrian, Silurian, Devonian, Carboniferous, and Permian volcanoes successively appeared, and their lavas and tuffs were carried down and buried under thousands of feet of sedimentary deposits.[80]

Torrents of Water and Mud.—We have seen that large quantities of water accompany many volcanic eruptions. In some cases, where ancient crater-lakes or internal reservoirs, shaken by repeated detonations, have been finally disrupted, the mud which has thereby been liberated has issued from the mountain. Such "mud-lava" (*lava d'acqua*), on account of its liquidity and swiftness of motion, is more dreaded for destructiveness than even the true melted lavas. On the other hand, rain or melted snow or ice, rushing down the cone and taking up loose volcanic dust, is converted into a kind of mud that grows more and more pasty as it descends. The mere sudden rush of such large bodies of water down the steep declivity of a volcanic cone cannot fail to effect much geological change. Deep trenches are cut out of the loose volcanic slopes, and sometimes large areas of woodland are swept away, the débris being strewn over the plains below.

One of these mud-lavas invaded Herculaneum during the great eruption of 79, and by quickly enveloping the houses and their contents, has preserved for us so many precious and perishable monuments of antiquity. In the same district, during the eruption of 1622, a torrent of this kind poured down upon the villages of Ottajano and Massa, overthrowing walls, filling up streets, and even burying houses with their inhabitants. During the great eruption of Cotopaxi, in June, 1877, enormous torrents of water and

[80] Presidential Addresses, Quart. Journ. Geol. Soc. xlvii. (1891), xlviii. (1892).

mud, produced by the melting of the snow and ice of the cone, rushed down from the mountain. Huge portions of the glaciers of the mountain were detached by the heat of the rocks below them and rushed down bodily, breaking up into blocks. The villages all round the mountain to a distance of sometimes more than ten geographical miles were left deeply buried under a deposit of mud mixed with blocks of lava, ashes, pieces of wood, lumps of ice, etc.[90] Many of the volcanoes of Central and South America discharge large quantities of mud directly from their craters. Thus, in the year 1691, Imbaburu, one of the Andes of Quito, emitted floods of mud so largely charged with dead fish that pestilential fevers arose from the subsequent effluvia. Seven years later (1698), during an explosion of another of the same range of lofty mountains, Carguairazo (14,706 feet), the summit of the cone is said to have fallen in, while torrents of mud containing immense numbers of the fish *Pymelodus Cyclopum*, poured forth and covered the ground over a space of four square leagues. The carbonaceous mud (locally called *moya*) emitted by the Quito volcanoes sometimes escapes from lateral fissures, sometimes from the craters. Its organic contents, and notably its siluroid fish, which are the same as those found living in the streams above ground, prove that the water is derived from the surface, and accumulates in craters or underground cavities until discharged by volcanic action. Similar but even more stupendous and destructive outpourings have taken place from the volcanoes of Java, where wide tracts of luxuriant vegetation have at different times been buried under masses of dark gray mud, sometimes 100 feet thick, with a rough

[90] Wolf, Neues Jahrb. 1878, p. 133.

hillocky surface from which the top of a submerged palm-tree would here and there protrude.

Between the destructive effects of mere water-torrents and that of these mud-floods there is, of course, the notable difference that, whereas in the former case a portion of the surface is swept away, in the latter, while sometimes considerable demolition of the surface takes place at first, the main result is the burying of the ground under a new tumultuous deposit by which the topography is greatly changed, not only as regards its temporary aspect, but in its more permanent features, such as the position and form of its water-courses.

Effects of the Closing of a Volcanic Chimney—Sills and Dikes.—A study of the volcanic phenomena of former geological periods, where the structure of the interior of volcanoes and their funnels has been laid bare by denudation, shows that in many cases a vent becomes plugged up by the ascent and consolidation of solid material in it, while yet the eruptive energy of the volcano, though lessened, has not ceased. A time is reached when the ascending magma, impelled by pressure from below, can no longer overcome the resistance of the column of solid lava or compacted agglomerate which has sealed up the orifice of discharge, or at least when it can more easily force a passage for itself between the sedimentary strata on which the whole volcanic pile may rest, or between the lava sheets at the base of the pile, or into fissures in either or both of these groups. Hence arise intrusive sheets or sills and dikes or veins (see pp. 952, 958). That these later manifestations of volcanic energy have sometimes taken place on a great scale is shown by the number and size of the sills which are found at the base of the Palæozoic volcanic groups of Britain. This feature is a remarkably striking feature of the rocks that underlie the great Lower Silurian volcanic outflows of Arenig and Cader Idris in North Wales. It recurs so frequently, not only among Palæozoic volcanic phenomena but quite as markedly among those of Tertiary age in the British Isles, that it must be regarded as marking an ordinary phase of volcanic action. But it remains of course invisible until in the progress of denudation a volcanic cone is cut down to the roots.

Exhalations of Vapors and Gases.—A volcano, as its activity wanes, may pass into the Solfatara stage, when only volatile emanations are discharged. The well-known Solfatara near Naples, since its last eruption in 1198, has constantly discharged steam and sulphurous vapors. The island of Volcano has now passed also into this phase, though giving vent to occasional explosions. Numerous other examples occur among the old volcanic tracts of Italy, where they have been termed *soffioni*. Steam, escaping in conspicuous jets, sulphuretted hydrogen, hydrochloric acid, and carbonic acid are particularly noticeable at these orifices. The vapors in rising condense. The sulphuretted hydrogen partially oxidizes into sulphuric acid, which powerfully corrodes the surrounding rocks. The lava or tuff through which the hot vapors rise is bleached into a white or yellowish crumbling clay, in which, however, the less easily corroded crystals may still be recognized *in situ*. At the same time, sublimates of sulphur or of chlorides may be formed, or the sulphuric acid attacking the lime of the silicates gives rise to gypsum, which spreads in a network of threads and veins through the hot, steaming, and decomposed mass. In this way, at the island of Volcano, obsidian is converted into a snow-white, dull, clay-stone-like substance, with crystals of sulphur and gypsum in its crevices. Silica is likewise deposited from solution at many orifices, and coats the altered rock with a crust of chalcedony, hyalite, or some form of siliceous sinter. As the result of this action, masses of rock are decomposed below the surface, and new deposits of alum, sulphur, sulphides of iron and copper, etc., are formed above them. Examples have been described from Iceland, Lipari, Hungary, Terceira, Teneriffe, St. Helena, and many other localities.[91] The *lagoons* of Tuscany are basins into which the waters from suffioni are discharged, and where a precipitation of their dissolved salts takes place. Among the substances thus deposited are gypsum, sulphur, silica, and various alkaline salts; but the most important is boracic acid, the extraction of which constitutes a thriving industry. In Chile many solfataras occur among extinct volcanoes.[92]

Another class of gaseous emanations betokens a condition of volcanic activity further advanced toward final extinction. In these, the gas is carbon-dioxide, either issuing directly from the rock or bubbling up with water which is often quite cold. The old volcanic districts of Europe furnish many examples. Thus on the shores of the Laacher See—an ancient crater-lake of the Eifel—the gas issues from numerous openings called *moffette*, round which dead insects, and occasionally mice and birds, may be found. In the same region occur hundreds of springs more or less charged with this gas. The famous Valley of Death in Java con-

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[91] Von Buch, "Canar. Inseln," p. 232. Hoffmann. Pogg. Ann. 1832, pp. 38, 40, 60. Bunsen, Ann. Chem. Pharm. 1847 (lxii.), p. 10. Darwin, "Volcanic Islands," p. 29. The name *Propylite*, as already mentioned (ante, p. 293) has been proposed by Rosenbusch to be restricted to certain andesites and allied rocks altered by solfataric action.

[92] Domeyko, Ann. Mines, ix. (7e. sér.). Large numbers of solfataras occur also in Iceland.

tains one of the most remarkable gas-springs in the world. It is a deep, bosky hollow, from one small space on the bottom of which carbon-dioxide issues so copiously as to form the lower stratum of the atmosphere. Tigers, deer, and wild-boar, enticed by the shelter of the spot, descend and are speedily suffocated. Many skeletons, including those of man himself, have been observed.

As a distinct class of gas-springs, we may group and describe here the emanations of volatile hydrocarbons, which, when they take fire, are known as Fire-wells. These are not of volcanic origin, but arise from changes within the solid rocks underneath. They occur in many of the districts where mud-volcanoes appear, as in northern Italy, on the Caspian, in Mesopotamia, in southern Kurdistan, and in many parts of the United States. It has been observed that they frequently rise in regions where beds of rock-salt lie underneath, and as that rock has been ascertained often to contain compressed gaseous hydrocarbons, the solution of the rock by subterranean water, and the consequent liberation of the gas, has been offered as an explanation of these fire-wells.

In the oil regions of Pennsylvania, certain sandy strata occur at various geological horizons whence large quantities of petroleum and gas are obtained (p. 254). In making the borings for oil-wells, reservoirs of gas as well as subterranean courses or springs of water are met with. When the supply of oil is limited but that of gas is large, a contest for possession of the bore-hole sometimes takes place between the gas and water. When the machinery is removed and the boring is abandoned, the contest is allowed to proceed unimpeded and results in the intermittent discharge of columns of water and gas to heights of 130 feet or more.

At night, when the gas has been lighted. the spectacle of one of these "fire-geysers" is inconceivably grand.[93]

Geysers.—Eruptive fountains of hot water and steam, to which the general name of Geysers (*i.e.* gushers) is given, from the examples in Iceland, which were the first to be seen and described, mark a declining phase of volcanic activity. The Great and Little Geysers, the Strokkr and other minor springs of hot water in Iceland, have long been celebrated examples. More recently another series has been discovered in New Zealand. But probably the most remarkable and numerous assemblage is that which has been brought to light in the northwest part of the territory of Wyoming, and which has been included within the "Yellowstone National Park"—a region set apart by the Congress of the United States to be forever exempt from settlement, and to be retained for the instruction of the people. In this singular region the ground in certain tracts is honeycombed with passages which communicate with the surface by hundreds of openings, whence boiling water and steam are emitted. In most cases, the water remains clear, tranquil, and of a deep green-blue tint, though many of the otherwise quiet pools are marked by patches of rapid ebullition. These pools lie on mounds or sheets of sinter, and are usually edged round with a raised rim of the same substance, often beautifully fretted and streaked with brilliant colors. The eruptive openings usually appear on small,

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[93] Ashburner, Proc. Amer. Phil. Soc. xvii. (1877), p. 127. Stowell's Petroleum Reporter, 15th Sept. 1879. Second Geol. Survey of Pennsylvania, containing Reports by J. Carll, 1877, 1880. J. S. Newberry, "The First Oil Well." Harper's Magazine, Oct. 1890. On the naphtha districts of the Caspian Sea, Abich, Jahrb. Geol. Reichs. xxix. (1879), p. 165. H. Sjögren, op. cit. xxxvii. (1887), p. 47. C. Marvin, "Region of Eternal Fire," London, 1884. See also for phenomena in Gallicia, Jahrb. Geol. Reichs. xv. pp. 199, 351; xvii. p. 291; xviii. p. 311; xxxi. (1881), p. 131. Proc. Inst. Civ. Engineers, xlii. (1875), p. 343.

low, conical elevations of sinter, from each of which one or more tubular projections rise. It is from these irregular tube-like excrescences that the eruptions take place.

The term geyser is restricted to active openings whence columns of hot water and steam are from time to time ejected; the non-eruptive pools are only hot springs. A true geyser should thus possess an underground pipe or passage, terminating at the surface in an opening built

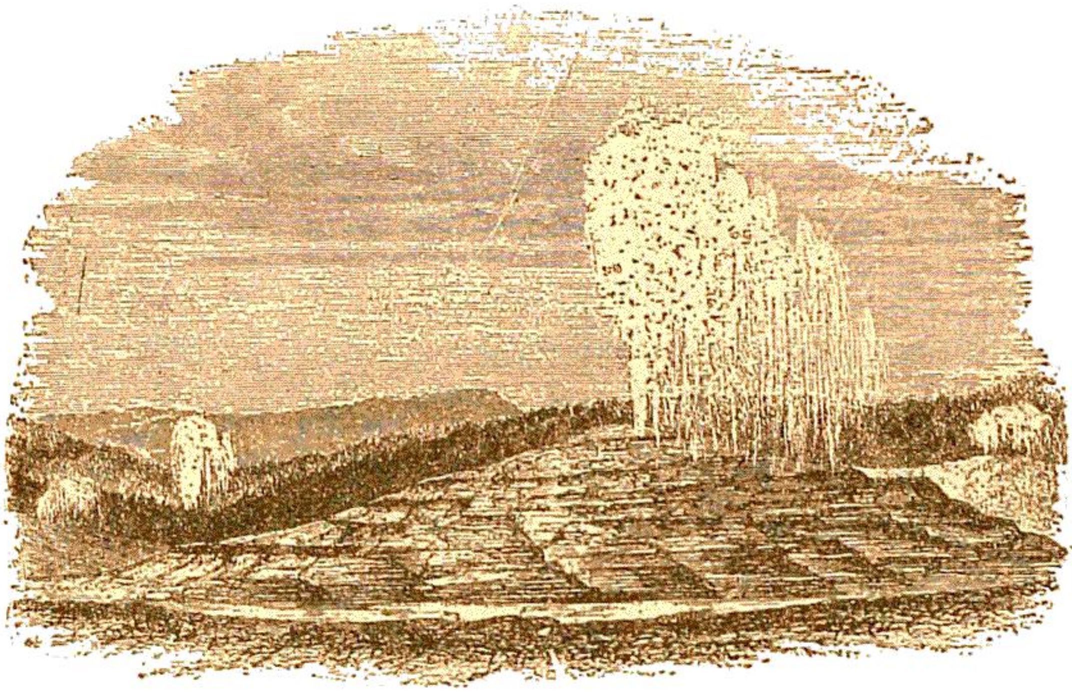

Fig. 52.—View of Old Faithful Geyser, and others in the distance, Fire Hole River, Yellowstone Park.

round with deposits of sinter. At more or less regular intervals, rumblings and sharp detonations in the pipe are followed by an agitation of the water in the basin, and then by the violent expulsion of a column of water and steam to a considerable height in the air. In the Upper Fire Hole basin of the Yellowstone Park, one of the geysers, named "Old Faithful" (Fig. 52), has ever since the discovery of the region sent out a column of mingled water and steam every sixty-three minutes or thereabout. The column rushes up with a loud roar to a height of more than 100 feet, the whole eruption not occupying more than about five or six minutes. The other geysers of the same district are more capricious in their movements, and some of them more stupendous in the volume of their discharge. The eruptions of the Castle, Giant, and Beehive vents are marvellously impressive.[94]

In examining the Yellowstone Geyser region in 1879, the author was specially struck by the evident independence of the vents. This was shown by their very different levels, as well as by their capricious and unsympathetic eruptions. On the same hill-slope, dozens of quiet pools, as well as some true geysers, were noticed at different levels, from the edge of the Fire Hole River up to a height of at least 80 feet above it. Yet the lower pools, from which, of course, had there been underground connection between the different vents, the drainage should have principally discharged itself, were often found to be quiet steaming pools without outlet, while those at higher points were occasionally in active eruption. It seemed also to make no difference in the height or tranquillity of one of the quietly boiling caldrons, when an active projection of steam and water was going on from a neighboring vent on the same gentle slope.

Bunsen and Descloiseaux spent some days experimenting at the Icelandic geysers, and ascertained that in the Great Geyser, while the surface temperature is about 212° Fahr., that of lower portions of the tube is much higher—a thermometer giving as high a reading as 266° Fahr. The water

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[94] See Hayden's Reports for 1870 and for 1878, in the latter of which will be found a voluminous monograph on the Hot Springs by A. C. Peale; Comstock's Report in Jones's Reconnoissance of N. W. Wyoming, etc., 1874. The deposits of hot springs are further referred to on pp. 267, 809.

at a little depth must consequently be 54° above the normal boiling-point, but it is kept in the fluid state by the pressure of the overlying column. At the basin, however, the water cools quickly. After an explosion it accumulates there, and eventually begins to boil. The pressure on the column below being thus relieved, a portion of the superheated water flashes into steam, and as the change passes down the pipe, the whole column of water and steam rushes out with great violence. The water thereafter gradually collects again in the pipe, and after an interval of some hours the operation is renewed. The experiments made by Bunsen proved the source of the eruptive action to lie in the hot part of the pipe. He hung stones by strings to different depths in the funnel of the geyser, and found that only those in the higher part were cast out by the rush of water, sometimes to a height of 100 feet, while, at the same time, the water at the bottom was hardly disturbed at all. These observations give much interest and importance to the phenomena of geysers in relation to volcanic action. They show that the eruptive force in geysers is steam; that the water column, even at a comparatively small depth, may have a temperature considerably above 212°; that this high temperature is local; and that the eruptions of steam and water take place periodically, and with such vigor as to eject large stones to a height of 100 feet.[95]

The hot water comes up with a considerable percentage of mineral matter in solution. According to the analysis of Sandberger, water from the Great Geyser of Iceland

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[95] Comptes Rendus, xxiii. (1846), p. 934; Pogg. Annal. lxxii. (1847), p. 159; lxxxiii. (1851), p. 197. Ann. Chimie, xxxviii. (1853), pp. 215, 385. The explanation proposed for the phenomena observed at the Great Geyser is probably not applicable in those cases where the mere local accumulation of steam in suitable reservoirs may be sufficient.

contains in 10,000 parts the following proportions of ingredients: silica, 5·097; sodium-carbonate, 1·939; ammonium-carbonate, 0·083; sodium-sulphate, 1·07; potassium-sulphate, 0·475; magnesium-sulphate, 0·042; sodium-chloride, 2·521; sodium-sulphide, 0·088; carbonic acid, 0·557=11·872.[96]

When the water has reached the surface, it deposits the silica as a sinter on the surfaces over which it flows or on which it rests.[97] The deposit, which is not due to mere cooling and evaporation, is curiously aided by the presence of living algæ (postea, p. 809). It naturally takes place fastest along the margins of the pools. Hence the curiously fretted rims by which these sheets of water are surrounded, and the tubular or cylindrical protuberances which rise from the growing domes. Where numerous hot springs have issued along a slope, a succession of basins gives a curiously picturesque terraced aspect to the ground, as at the Mammoth Springs of the Yellowstone Park and at the now destroyed terraces of Rotamahana in New Zealand.

In course of time, the network of underground passages undergoes alteration. Orifices that were once active cease to erupt, and even the water fails to overflow them. Sinter is no longer formed round them, and their surfaces, exposed to the weather, crack into fine shaly rubbish like comminuted oyster-shells. Or the cylinder of sinter grows upward until, by the continued deposit of sinter and the failing force of the geyser, the tube is finally filled up, and then a dry and crumbling white pillar is left to mark the site of the extinct geyser.

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[96] Annal. Chem. und Pharm. 1847, p. 49. A series of detailed analyses of the hot springs of the Yellowstone National Park will be found in No. 47 of the Bull. U. S. Geol. Surv. 1888.

[97] For an account of the geyserite of the Yellowstone district, see papers by W. H. Weed, Amer. Journ. Sci. xxxvii. (1889), and 9th Ann. Rep. U. S. Geol. Surv. 1890.

Mud-Volcanoes.—These are of two kinds: 1st, where the chief source of movement is the escape of gaseous discharges; 2d, where the active agent is steam.

(1) Although not volcanic in the proper sense of the term, certain remarkable orifices of eruption may be noticed here, to which the names of *mud-volcanoes*, *salses*, *air-volcanoes*, and *maccalubas* have been applied (Sicily, the Apennines, Caucasus, Kertch, Tamar). These are conical hills formed by the accumulation of fine and usually saline mud, which, with various gases, is continuously or intermittently given out from the orifice or crater in the centre. They occur in groups, each hillock being sometimes less than a yard in height, but ranging up to elevations of 100 feet or more. Like true volcanoes, they have their periods of repose, when either no discharge takes place at all, or mud oozes out tranquilly from the crater, and their epochs of activity, when large volumes of gas, and sometimes columns of flame, rush out with considerable violence and explosion, and throw up mud and stones to a height of several hundred feet. The gases play much the same part, therefore, in these phenomena that steam does in those of true volcanoes. They consist of marsh-gas and other hydrocarbons, carbon-dioxide, sulphuretted hydrogen, and nitrogen, with petroleum vapors. The mud is usually cold. In the water occur various saline ingredients, among which common salt generally appears; hence the name, *Salses*. Naphtha is likewise frequently present. Large pieces of stone, differing from those in the neighborhood, have been observed among the ejections, indicative doubtless of a somewhat deeper source than in ordinary cases. Heavy rains may wash down the minor mud-cones and spread out the material over the ground; but gas-bubbles again appear

through the sheet of mud, and by degrees a new series of mounds is once more thrown up.

There can be little doubt that this type of mud-volcano is to be traced to chemical changes in progress underneath. Dr. Daubeny explained them in Sicily by the slow combustion of beds of sulphur. The frequent occurrence of naphtha and of inflammable gas points, in other cases, to the disengagement of hydrocarbons from subterranean strata.[98]

(2) The second class of mud-volcano presents itself in true volcanic regions, and is due to the escape of hot water and steam through beds of tuff or some other friable kind of rock. The mud is kept in ebullition by the rise of steam through it. As it becomes more pasty and the steam meets with greater resistance, large bubbles are formed which burst, and the more liquid mud from below oozes out from the vent. In this way, small cones are built up, many of which have perfect craters atop. In the Geyser tracts of the Yellowstone region, there are instructive examples of such active and extinct mud-vents. Some of the extinct cones there are not more than a foot high, and might be carefully removed as museum specimens.

Mud-volcanoes occur in Iceland, Sicily (Maccaluba), in many districts of northern Italy, at Tamar and Kertch, at Baku on the Caspian, near the mouth of the Indus, and in other parts of the globe.[99]

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[98] The "burning hills" of Turkestan are referred to the subterranean combustion of beds of Jurassic Coal. J. Muschketoff, Neues Jahrb. 1876, p. 516.

[99] On mud-volcanoes, see Bunsen, Liebig's Annual, lxiii. (1847), p. 1; Abich, Mem. Acad. St. Petersburg, 7e. ser. t. vi. No. 5, ix. No. 4; Daubeny's "Volcanoes," pp. 264, 539; Buist, Trans. Bombay Geograph. Soc. x. p. 154; Roberts, Journ. Roy. Asiatic Soc. 1850; De Verneuil, Mem. Soc. Geol. France, iii. (1838), p. 4; Stiffe, Q. J. Geol. Soc. xxx. p. 50; Von Lasaulx, Z. Deutsch. Geol. Ges. xxxi. p. 457; Gümbel, Sitzb. Akad. Münch. 1879; F. R. Mallet, Rec. Geol. Surv. India, xi. p. 188. H. Sjögren, Jahrb. Geol. Reichsanst. xxxvii. (1887), p. 233.

§ 3. Structure of Volcanoes

We have now to consider the manner in which the various solid materials ejected by volcanic action are built up at the surface. This inquiry will be restricted here to the phenomena of modern volcanoes, including the active and dormant, or recently extinct, phases. Obviously, however, in a modern volcano we can study only the upper and external portions, the deeper and fundamental parts being still concealed from view. But the interior structure has been, in many cases, laid open among the volcanic products of ancient vents. As these belong to the architecture of the terrestrial crust, they are described in Book IV. The student is therefore requested to take the descriptions there given, in connection with the foregoing and present sections, as related chapters of the study of volcanism.

Confining attention at present to modern volcanic action, we find that the solid materials emitted from the earth's interior are arranged in two distinct types of structure, according as the eruptions proceed from large central cones or from less prominent vents connected with fissures. In the former case, volcanic cones are produced; in the latter, volcanic plateaus or plains. The type of the volcanic cone, or ordinary volcano, is now the most abundant and best known.

i. *Volcanic Cones*

From some weaker point of a fissure, or from a vent opened directly by explosion, volcanic discharges of gas and vapors with their liquid and solid accompaniments make their way to the surface and gradually build up a volcanic hill or mountain. Occasionally, eruptions have proceeded no further than the first stage of gaseous explosion. A caldron-like cavity has been torn open in the ground, and ejected fragments of the solid rocks, through which the explosion has emerged, have fallen back into and round the vent. Subsequently, after possible subsidence of the fragmentary materials in the vent, and even of the sides of the orifice, water supplied by rain and filtering from the neighboring ground may partially, or wholly, fill up the cavity, so as to produce a lake either with or without a superficial outlet. Under favorable circumstances, vegetation creeping over bare earth and stone may so conceal all evidence of the original volcanic action as to make the quiet sheet of water look as if it had always been an essential part of the landscape. Explosion-lakes (Crater-lakes) of this kind occur in districts of extinct volcanoes, as in the Eifel (*maare*), central Italy, and Auvergne. The crateriform hollow called the Gour de Tazenat, in Velay, has a diameter of half a mile and lies in the granite, while another cavity near Confolens, on the left bank of the Loire, has also been blown out of the granite and has given passage to no volcanic materials, but only to broken-up granite.[100] Other illustrations in central France are to be found in the Lakes of Pavin, Mont Sineire, Chauvet, Beurdouse, Champedaze and La Godival.[101] A remarkable example is supplied by the Lonar Lake in the Indian peninsula, half-way between Bombay and Nagpur. It lies in the midst of the volcanic plateau of the Deccan traps, which extend around it for hundreds of miles in nearly flat beds that slightly dip away from the lake. An almost circular

[100] Tournaire, Bull. Soc. Geol. France, xxvi. (1869), p. 1166; Daubrée, Comptes rend. 1890, p. 859.

[101] Scrope, "Volcanoes of Central France," pp. 81, 143, 144.

depression, rather more than a mile in diameter, and from 300 to 400 feet deep, contains at the bottom a shallow lake of bitter saline water, depositing crystals of trona (native carbonate of soda), the *nitrum* of the ancients. Except to the north and northeast, it is encircled with a raised rim of irregularly piled blocks of basalt, identical with that of the beds through which the cavity has been opened. The rim never exceeds 100 feet, and is often not more than 40 or 50 feet in height, and cannot contain a thousandth part of the material which once filled the crater. No other evidence of volcanic discharge from this vent is to be seen. Some of the contents of the cavity may have been ejected in fine particles, which have subsequently been removed by denudation; but it seems more probable that the existence of the cavity is mainly due to subsidence after the original explosion.[102]

In most cases, explosions are accompanied by the expulsion of so much solid material that a cone gathers round the point of emission. As the cone increases in height, by successive additions of ashes or lava to its surface, these volcanic sheets are laid down upon progressively steeper slopes. The inclination of beds of lava, which must have originally issued in a more or less liquid condition, offered formerly a difficulty to observers, and suggested the famous theory of Elevation-craters (*Erhebungskratere*) of L. von Buch,[103] Elie de Beaumont,[104] and other geologists.

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[102] This cavity may possibly mark one of the vents from which the basalt floods issued. On explosion-craters and lakes, see Scrope's "Volcanoes." Lecoq, "Epoques geologiques de l'Auvergne," tome iv.; compare also Vogelsang, "Vulcane der Eifel," and in Neues Jahrb. 1870, pp. 199, 326, 460. On Lonar Lake, see Malcolmson, Trans. Geol. Soc. 2d ser. v. p. 562. Medlicott and Blanford's "Geology of India," p. 379.

[103] Pogg. Ann. ix., x., xxvii. p. 169.

[104] Bull. Soc. Geol. France, iv. p. 357. Ann. des Mines, ix. and x.

According to this theory, the conical shape of a volcanic cone arises mainly from an upheaval or swelling of the ground, round the vent from which the materials are finally expelled. A portion of the earth's crust (represented in Fig. 53 as composed of stratified deposits, *a b g h*) was believed to have been pushed up like a huge blister, by forces acting from below (at *c*) until the summit of the dome gave way and volcanic materials were emitted. At first these might only partially fill the cavity (as at *f*), but subsequent eruptions, if sufficiently copious, would cover over

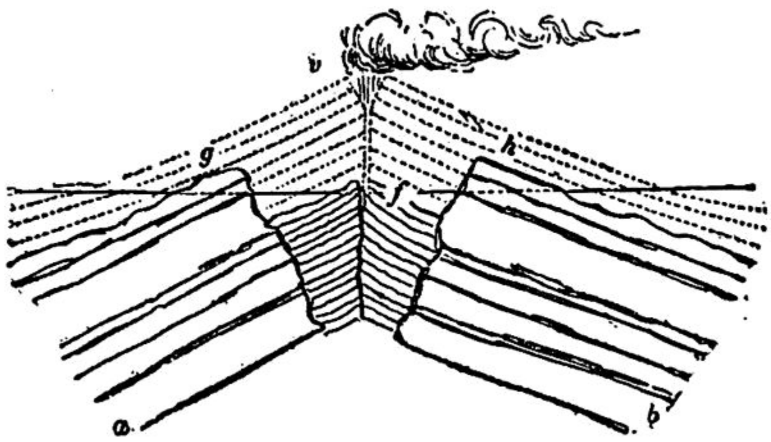

Fig. 53.—Section illustrative of the Elevation-crater Theory.

the truncated edges of the pre-volcanic rocks (as at *g h*), and would be liable to further upheaval by a renewal of the original upward swelling of the site.

It was a matter of prime importance in the interpretation of volcanic action to have this question settled. To Poulett Scrope, Constant Prévost, and Lyell, belong the merit of disproving the Elevation-crater theory. Scrope showed conclusively that the steep slope of the lava-beds of a volcanic cone was original.[105] Constant Prévost pointed out that there was no more reason why lava should not consolidate

105 "Considerations on Volcanoes," 1825. Quart. Journ. Geol. Soc. xii. p. 326.

on steep slopes than that tears or drops of wax should not do so.[106] Lyell, in successive editions of his works, and subsequently by an examination of the Canary Islands with Hartung, brought forward cogent arguments against the Elevation-crater theory.[107] A comparison of Fig. 53 with Fig. 54 will show at a glance the difference between

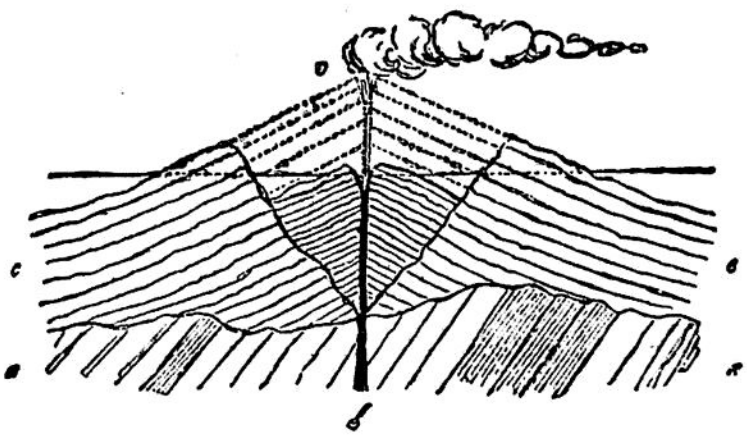

Fig. 54.—Diagram-section of a normal Volcano.

x x, Pre-volcanic platform, supposed here to consist of upraised stratified rocks, broken through by the funnel *f*, from which the cone of volcanic materials *c c* has been erupted. Inside the crater *v*, previously cleared by some great explosion, a minor cone may be formed during feebler phases of volcanic action, and this inner cone may increase in size until the original cone is built up again, as shown by the dotted lines.

this theory and the views of volcanic structure now universally accepted. The steep declivities on which lava can actually consolidate have been referred to on p. 386.

The conical form of a volcano is that naturally assumed by a self-supporting mass of coherent material. It varies slightly according to the nature of the materials of the cone, the progress of atmospheric denudation, the position of the crater, the direction in which materials are ejected, the force and direction of the wind during an eruption, the growth

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[106] Comptes Rendus, i. (1835), 460; xli. (1855), p. 919. Geol. Soc. France: Memoires, ii. p. 105, and Bull. xiv. 217. Societe Philom. Paris, Proc. Verb. 1843, p. 13.

[107] Phil. Trans, 1858, p. 703. See the remarks of Fouqué, "Santorin," pp. 400–422.

of parasitic cones, and the collapse due to the dying out of volcanic energy.[108]

The cone grows by additions made to its surface during successive eruptions, and though liable to great local variation of contour and topography, preserves its general form with singular persistence. Many exaggerated pictures have been drawn of the steepness of slope in volcanic cones, but it is obvious that the angle cannot as a whole exceed the maximum inclination of repose of the detrital matter ejected from the central chimney.[109] A series of profiles of volcanic cones taken from photographs shows how nearly they approach to a common average type.[110] One of the most potent and constant agencies in modifying the outer forms of these cones is undoubtedly to be found in rain and torrents, which sweep down the loose detritus and excavate ravines on the declivities till a cone may be so deeply trenched as to resemble a half-opened umbrella.[111]

The crater doubtless owes its generally circular form to the equal expansion in all directions of the explosive vapors from below. In some of the mud-cones already noticed, the crater is not more than a few inches in diameter and depth. From this minimum, every gradation of size may be met with, up to huge precipitous depressions, a mile or more in diameter, and several thousand feet in depth. In the crater of an active volcano, emitting lava and scoriæ, like Vesuvius, the walls are steep, rugged cliffs of scorched and

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[108] J. Milne, Geol. Mag. 1878, p. 339; 1879, p. 506. Seismolog. Soc. Japan, ix. p. 179. G. F. Becker, Amer. Journ. Sci. xxx. 1885, p. 283.

[109] Cotopaxi is a notable example of such exaggerated representation. Mr. Whymper found that the general angles of the northern and southern slopes of the cone were rather less than 30° ("Travels amongst the Great Andes," p. 123). Humboldt depicted the angle as one of 50°!

[110] See Milne, Seism. Soc. Japan, ix., and Geol. Mag. 1878, plate ix.

[111] On the denudation of volcanic cones, see H. J. Johnston-Lavis, Q. J. Geol. Soc. xl. p. 103.

blasted rock—red, yellow, and black. Where the material erupted is only loose dust and lapilli, the sides of the crater are slopes, somewhat steeper than those of the outside of the cone.

The crater-bottom of an active volcano of the first class, when quiescent, forms a rough plain dotted over with hillocks or cones, from many of which steam and hot vapors are ever rising. At night, the glowing lava may be seen lying in these vents, or in fissures, at a depth of only a few feet from the surface. Occasional intermittent eruptions take place and miniature cones of slag and scoriæ are thrown up. In some instances, as in the vast crater of Gurung Tengger, in Java, the crater-bottom stretches out into a wide level waste of volcanic sand, driven by the wind into dunes like those of the African deserts.

A volcano commonly possesses one chief crater, often also many minor ones, of varying or of nearly equal size. The volcano of the Isle of Bourbon (or Réunion) has three craters.[112] Not infrequently craters appear successively, owing to the blocking up of the pipe below. Thus in the accompanying plan of the volcanic cone of the island of Volcanello (Fig. 55), one of the Lipari group, the volcanic funnel has shifted its position twice, so that three craters have successively appeared upon the cone, and partially overlap each other. It may be from this cause that some

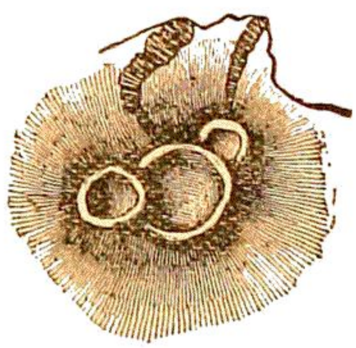

Fig. 55.—Plan of Volcanello, showing three successive craters.

[112] For recent information regarding this volcanic island, see R. von Drasche, in Verhandl. Geol. Reichsanst. 1875, p. 266, and in Tschermak's Min. Mittheil. 1875 (3), p. 217 (4), p. 39, and his work "Die Insel Réunion (Bourbon)," 4to, Vienna, 1878. C. Vélain, "Description geologique de la Presqu'ile d'Aden, de l'Ile de la Réunion, etc.," Paris, 4to, 1878; and his work, "Les Volcans," 1884.

volcanic mountains are now destitute of craters, or in other cases, because the lava has welled up in dome form covered perhaps with masses of scoriæ, but without the production of a definite crater. Mount Ararat, for example, is said to have no crater; but so late as the year 1840 a fissure opened on its side whence a considerable eruption took place. The trachytic puys of Auvergne are dome-shaped hills without craters.

Though the interior of modern volcanic cones can be at the best but very partially examined, the study of the sites of long-extinct cones, laid bare after denudation, shows that subsidence of the ground has commonly taken place at and round a vent. Evidence of subsidence has also been observed at some modern volcanoes (*ante*, p. 395). Theoretically two causes may be assigned for this structure. In the first place, the mere piling up of a huge mass of material round a given centre tends to press down the rock underneath, as some railway embankments may be observed to have done. This pressure must often amount to several hundred tons on the square foot. In the second place, the expulsion of volcanic material to the surface may leave cavities underneath, into which the overlying crust will naturally gravitate. These two causes combined, as suggested by Mr. Mallet, afford a probable explanation of the saucer-shaped depressions in which many ancient and some modern vents appear to lie.[113]

The following are the more important types of volcanic cones:[114]

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[113] Mallet, Q. J. Geol. Soc. xxxiii. p. 740. See also the account of "Volcanic Necks," in Book IV. Part VII.

[114] Von Seebach (Z. Deutsch. Geol. Ges. xviii. 644) distinguished two volcanic types. 1st, Bedded Volcanoes (Strato-Vulkane), composed of successive sheets of lava and tuffs, and embracing the great majority of volcanoes. 2d, Dome Volcanoes, forming hills composed of homogeneous protrusions of

1. **Cones of Non-volcanic Materials.**—These are due to the discharge of steam or other aeriform product through the solid crust without the emission of any true ashes or lava. The materials ejected from the cavity are wholly, or almost wholly, parts of the surrounding rocks through which the volcanic pipe has been drilled. Some of the cones surround-

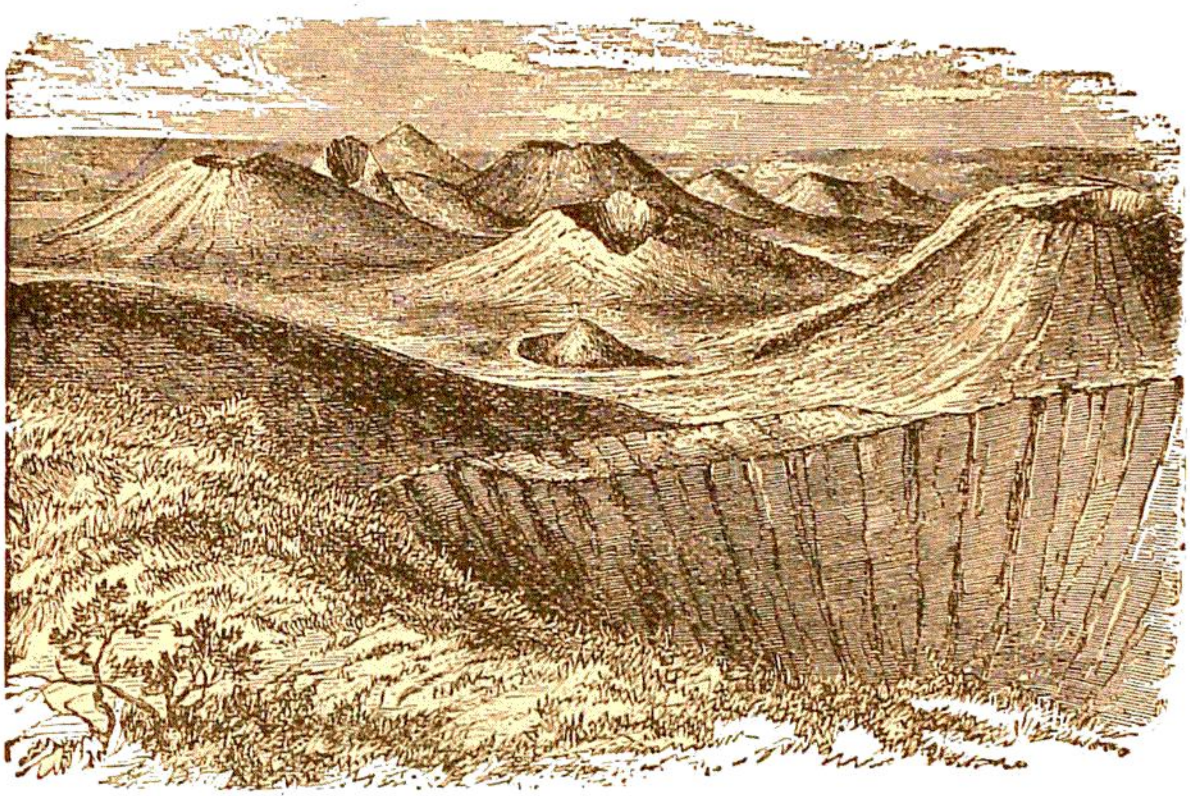

Fig. 56—View of the Tuff-cones of Auvergne, taken from the top of the cone and crater of Puy Pariou.

ing the crater lakes (*maare*) of the Eifel consist chiefly of fragments of the underlying Devonian slates (pp. 341, 363).

2. **Tuff-Cones, Cinder-Cones.**—Successive eruptions of fine dust and stones, often rendered pasty by mixture with the water so copiously condensed during an eruption, form a cone in which the materials are solidified by pressure into tuff. Cones made up only of loose cinders, like Monte Nuovo in the Bay of Baiæ, often arise on the flanks or round the roots of a great volcano, as happens to a small extent on Vesuvius, and on a larger scale upon Etna. They

lava, with little or no accompanying fragmentary discharges, without craters or chimneys, or at least with only minor examples of these volcanic features. He believed that the same volcano might at different periods in its history belong to one or other of these types—the determining cause being the nature of the erupted lava, which, in the case of the dome volcanoes, is less fusible and more viscid than in that of the bedded volcanoes. (See below, under "Lava-cones.")

likewise occur by themselves apart from any lava-producing volcano, though usually they afford indications that columns of lava have risen in their funnels, and even now and then that this lava has reached the surface.

The cones of the Eifel district have long been celebrated for their wonderful perfection. Though small in size, they exhibit with singular clearness many of the leading features of volcanic structure. Those of Auvergne are likewise exceedingly instructive.[115] The high plateaus of Utah are dotted with hundreds of small volcanic cinder-cones, the singular positions of which, close to the edge of profound river-gorges and on the upthrow side of faults, have already (p. 348) been noticed. Among the Carboniferous volcanic rocks of central Scotland the stumps of ancient tuff-cones, frequently with a central core of basalt, or with dikes and veins of that rock, are of common occurrence.[116]

The materials of a tuff-cone are arranged in more or less regularly stratified beds. On the outer side, they dip down the slopes of the cone at the average angle of repose, which

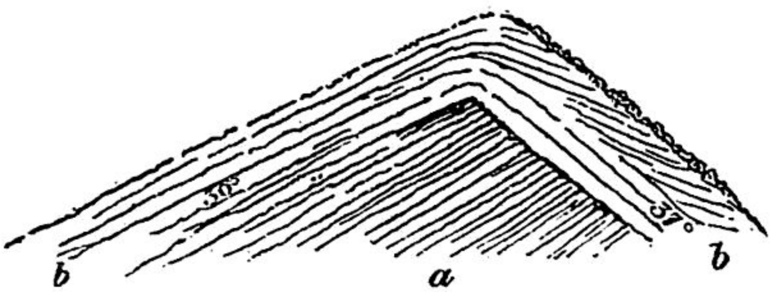

Fig. 57.—Section of the crater-rim of the Island of Volcano. *a*, Older tuff; *b b*, younger ashes; the crater lies to the right.

may range between 30° and 40°. From the summit of the crater-lip they likewise dip inward toward the crater-bottom at similar angles of inclination (Fig. 57).

3. **Mud-Cones** resemble tuff-cones in form, but are usually smaller in size and less steep. They are produced by the hardening of successive outpourings of mud from the orifices already described (p. 407). In the region of the Lower Indus, where they are abundantly distributed over an area

[115] For Auvergne, see works cited on p. 374. For the Eifel, consult Hibbert, "History of the Extinct Volcanoes of the Basin of Neuwied on the Lower Rhine," Edin. 1832. Von Dechen, "Geognostischer Führer zu dem Laacher See," Bonn, 1864. "Geognostischer Führer in das Siebengebirge am Rhein," Bonn, 1861.

[116] Trans. Roy. Soc. Edin. xxix. p. 455. See postea, Book IV. Part VII.

of 1000 square miles, some of them attain a height of 400 feet, with craters 30 yards across.[117]

4. **Lava-cones.**—Volcanic cones composed entirely of lava are comparatively rare, but occur in some younger Tertiary and modern volcanoes. Fouqué describes the lava of 1866 at Santorin as having formed a dome-shaped elevation, flowing out quietly and rapidly without explosions. After several days, however, its emission was accompanied with copious discharges of fragmentary materials and the formation of several crateriform mouths on the top of the dome. Where lava possesses extreme liquidity, and gives rise to little or no fragmentary matter, it may build up a flat cone as in the remarkable examples described by

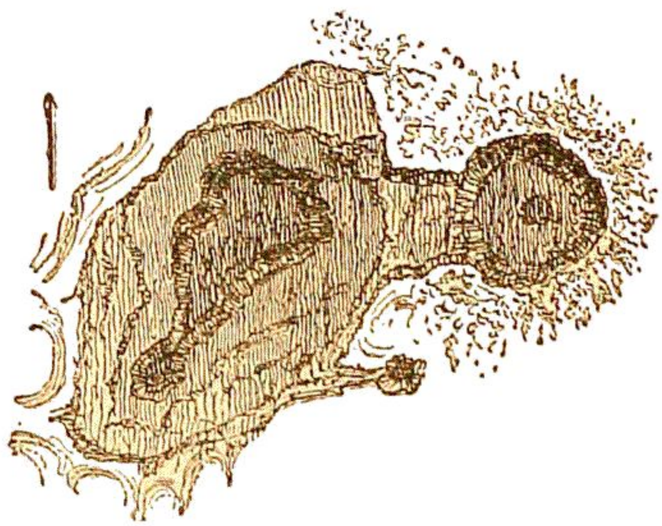

Fig. 59.—Plan of Lava-caldron, Kilauea, Hawaii (Dana, 1841[119]).

Dana from the Hawaii Islands.[118] On the summit of Mauna Loa (Fig. 58), a flat lava-cone 13,760 feet above the sea, lies a crater, which in its deepest part is about 8,000 feet broad, with vertical walls of stratified lava rising on one side to a height of 784 feet above the black lava-plain of the crater-bottom. From the edges of this elevated caldron, the mountain slopes outward at an angle of not more than 6°, until, at a level of about 10,000 feet lower, its surface is indented

Fig. 58—Profile of Lava-domes of Hawaii.

[117] Lyell, "Principles," ii. p. 77.

[118] In Wilkes's Report of U. S. Exploring Expedition, 1838–42, and Dana's "Characteristics of Volcanoes." See the works cited on p. 350.

[119] For more recent maps showing the variations of this crater, see Dana's "Characteristics."

by the vast pit-crater, Kilauea, about two miles long, and nearly a mile broad. So low are the surrounding slopes that these vast craters have been compared to open quarries on a hill or moor. The bottom of Kilauea is a lava-plain, dotted with lakes of extremely fluid lava in constant ebullition. The level of the lava has varied, for the walls surrounding the fiery flood consist of beds of similar lava, and are marked by ledges or platforms (Fig. 59) indicative of former successive heights of lava, as lake terraces show former levels of water. In the accompanying section (Fig. 60) the walls rising above the lower pit (*p p'*) were found to be 342 feet high, those bounding the higher terrace (*o n n' o'*) were 650 feet high, all being composed of innumerable beds of lava, as in cliffs of stratified rocks. Much of the bottom of the lower lava-plain has been crusted over by the solidification of the molten rock. But large areas, which shift

Fig. 60.—Section of Lava-terraces in Kilauea (Dana).

their position from time to time, remain in perpetual rapid ebullition. The glowing flood, as it boils up with a fluidity more like that of water than what is commonly shown by molten rock, surges against the surrounding terrace walls. Large segments of the cliffs, undermined by the fusion of their base, fall at intervals into the fiery waves and are soon melted. Recent observations by Captain Dutton point to a diminution of the activity of this lava-crater. In Iceland, and in the Western Territories of North America, low domes of lava appear to mark the vents from which extensive basalt floods have issued.

Where the lava assumes a more viscid character, as in trachyte and liparite, dome-shaped eminences may be protruded. As the mass increases in size by the advent of fresh material injected from below, the outer layer will be pushed outward, and successive shells will in like manner be enlarged as the eruption advances. On the cessation of discharges, we may conceive that a volcanic hill formed in this way will present an onion-like arrangement of its component sheets of rock. More or less perfect examples of this structure have been observed in Bohemia, Auvergne, and the Eifel.[120] The trachytic domes of Auvergne form a conspicuous feature among the cinder cones of that region. Huge conical protuberances of granophyre occur among the Tertiary volcanic rocks of the Inner Hebrides, and similar hills of liparite rise through the basalts of Iceland.

5. **Cones of Tuff and Lava.**—This is by far the most abundant type of volcanic structure, and includes the great volcanoes of the globe. Beginning, perhaps, as mere tuff-cones, these eminences have gradually been built up by successive

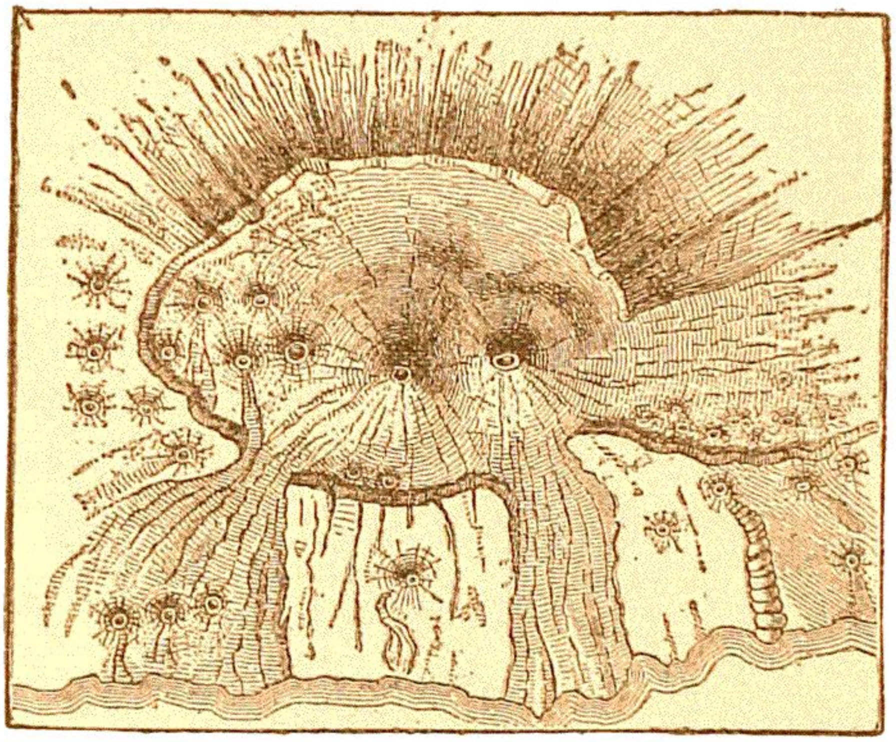

Fig. 61.—Plan of the Peak of Teneriffe, showing the large crater and minor cones.

outpourings of lava from different sides, and by showers of dust and scoriæ. At first, the lava, if the sides of the cone are strong enough to resist its pressure, may rise until it overflows from the crater. Subsequently, as the funnel becomes choked up, and the cone is shattered by repeated explosions, the lava finds egress from different fissures and openings on the cone. As the mountain increases in height, the number of lava-currents from its summit will usually

[120] E. Reyer (Jahrb. Geol. Reichs. 1879, p. 463) has experimentally imitated the process of extrusion by forcing up plaster of Paris through a hole in a board. For drawings of the Puy de Sarcouy and other dome-shaped hills which presumably have had this mode of origin, see Scrope's "Geology and Extinct Volcanoes of Central France." Refer also to the remarks already made on the liquidity of lava (ante, pp. 378–384), and the account of "Vulkanische Kuppen," postea, p. 433.

decrease. Indeed, the taller a volcanic cone grows, the less frequently as a rule does it erupt. The lofty volcanoes of the Andes have each seldom been more than once in eruption during a century. The Peak of Teneriffe (Fig. 61) was three times active during 370 years prior to 1798.[121] The

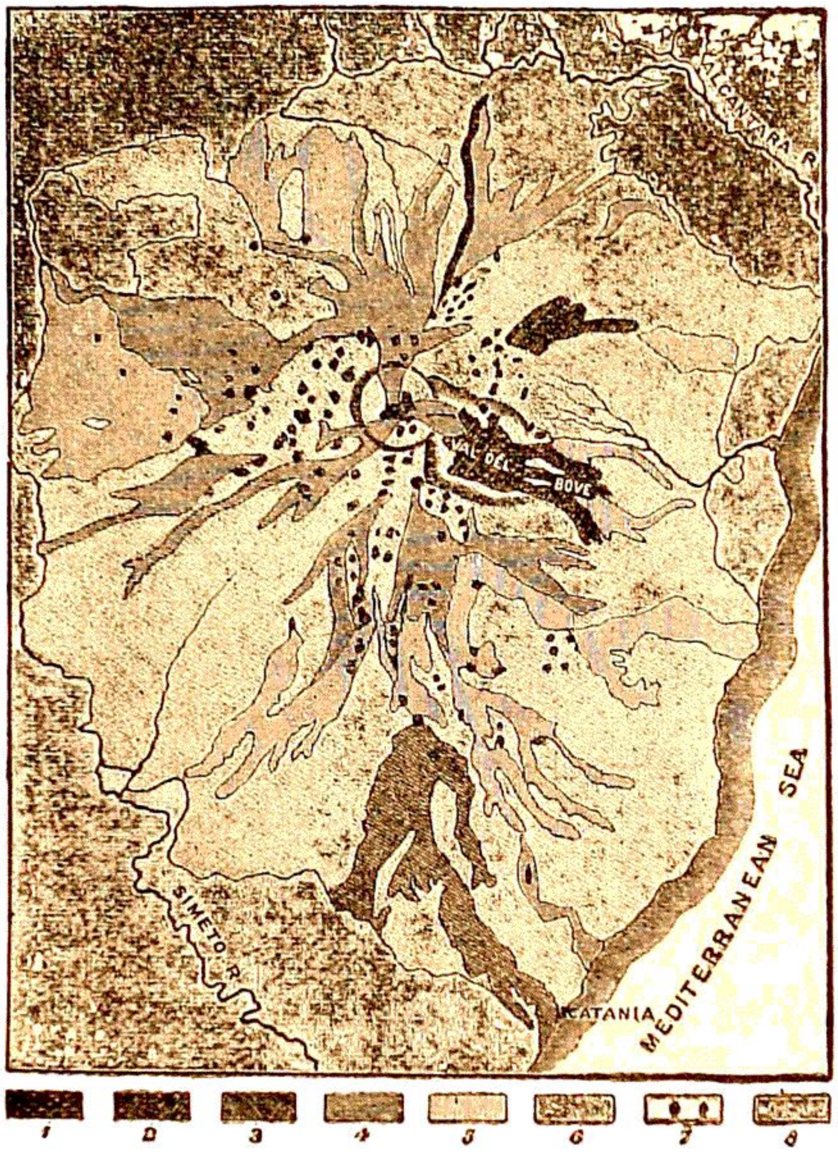

Fig. 62.—Map of Etna, after Sartorius von Waltershausen.
1, Lava of 1879; 2. Lavas of 1865 and 1852; 3, Lava of 1669; 4, Recent Lavas; 5, Lavas of the Middle Ages; 6, Ancient Lavas of unknown date; 7, Cones and Craters; 8, Non-volcanic Rocks.

earlier efforts of a volcano tend to increase its height, as well as its breadth; the later eruptions chiefly augment the breadth, and are often apt to diminish the height by blowing away the upper part of the cone. The formation of fissures and the consequent intrusion of a network of lava-

[121] For a recent account of Teneriffe, see A. Rothpletz, Petermann's Mittheil. xxxv. (1889), p. 237.

dikes, tend to bind the framework of the volcano and strengthen it against subsequent explosions. In this way, a kind of oscillation is established in the form of the cone, periods of crater-eruptions being succeeded by others when the emissions take place only laterally (*ante*, p. 359).

One consequence of lateral eruption is the formation of minor parasitic cones on the flanks of the parent volcano (p. 329). Those on Etna, more than 200 in number, are really miniature volcanoes, some of them reaching a height of 700 feet (Fig. 62). As the lateral vents successively become extinct, the cones are buried under sheets of lava and showers of débris thrown out from younger openings or from the parent cone. It sometimes happens that the original funnel is disused, and that the eruptions of the volcano take place from a newer main vent. Vesuvius, for example (as shown in Figs. 63 and 45), stands on the site of a portion of the rim of the more ancient and much larger vent of Monte Somma. The present crater of Etna lies to the northwest of the former vaster crater. The pretty little example of this shifting furnished by Volcanello has been already noticed (p. 415).

Fig. 63.—Section of Vesuvius and Monte Somma from north to south.

a, Plain of the Campagna; *b*, Village of Somma (413 French ft.); *c*, Fontana dell' Olivella (994); *d*, Casa Cancaroni (1588); *e*, Punta di Nasone (3430), on crest of old crater of Monte Somma; *f*, Atrio del Cavallo, bottom of old crater of Monte Somma; *g*, *i*, edges of modern crater (*h*) of Vesuvius (3640); *k*, Boche Nuove (1515); *l*, Camaldoli (584); *m*, Torre dell' Annunziata, on Bay of Naples.

While, therefore, a volcano, and more particularly one of great size, throwing out both lava and fragmentary materials, is liable to continual modification of its external form, as the result of successive eruptions, its contour is likewise usually exposed to extensive alteration by the effects of ordinary atmospheric erosion, as well as from the condensation of the volcanic vapors. Heavy and sudden floods, produced by the rapid rainfall consequent upon a copious discharge of steam, rush down the slopes with such volume and force as to cut deep gullies in the loose or only partially consolidated tuffs and scoriæ. Rain continues the erosion until the outer slopes, unless occasionally renewed by fresh showers of detritus, assume a curiously furrowed aspect, like a half-opened umbrella, the ridges being separated by furrows that narrow upward toward the summit of the cone. The outer declivities of Monte Somma afford an excellent illustration of this form of surface, the numerous ravines on that side of the mountain presenting instructive sections of the prehistoric lavas and tuffs of the earlier and more important period in the history of this volcano.[122] Similar trenches have been eroded on the southern or Vesuvian side of the original cone, but these have in great measure been filled up by the lavas of the younger mountain. The ravines, in fact, form natural channels for the lava, as may unfortunately be seen round the Vesuvian observatory. This building is placed on one of the ridges between two deep ravines; but the lava-streams of recent years have poured into these ravines on either side, and are rapidly filling them up.

Submarine Volcanoes.—It is not only on the surface of the land that volcanic action shows itself. It takes place likewise under the sea, and as the geological records of the earth's past history are chiefly marine formations, the characteristics of submarine volcanic action have no small interest for the geologist. In a few instances, the actual outbreak of a submarine eruption has been witnessed. Thus, in the early summer of 1783, a volcanic eruption took place about thirty miles from Cape Reykjanaes on the west coast of Iceland. An island was built up, from which fire and smoke continued to issue, but in less than a year the waves have washed the loose pumice away, leaving a submerged reef from five to thirty fathoms below sea-level. About a month after this eruption, the frightful outbreak of Skaptar Jökull, already referred to (p. 378), began, the distance of this mountain from the submarine vent being nearly 200 miles.[123] A century afterward, viz. in July, 1884, another

[122] See H. J. Johnston-Lavis, Q. J. Geol. Soc. xl. p. 103.
[123] Lyell, "Principles," ii. p. 49.

volcanic island is said to have been thrown up near the same spot, having at first the form of a flattened cone, but soon yielding to the power of the breakers. Many submarine eruptions have taken place within historic times in the Mediterranean. The most noted of these occurred in the year 1831, when a new volcanic island (Graham's Island, Ile Julia) was thrown up, with abundant discharge of steam and showers of scoriæ, between Sicily and the

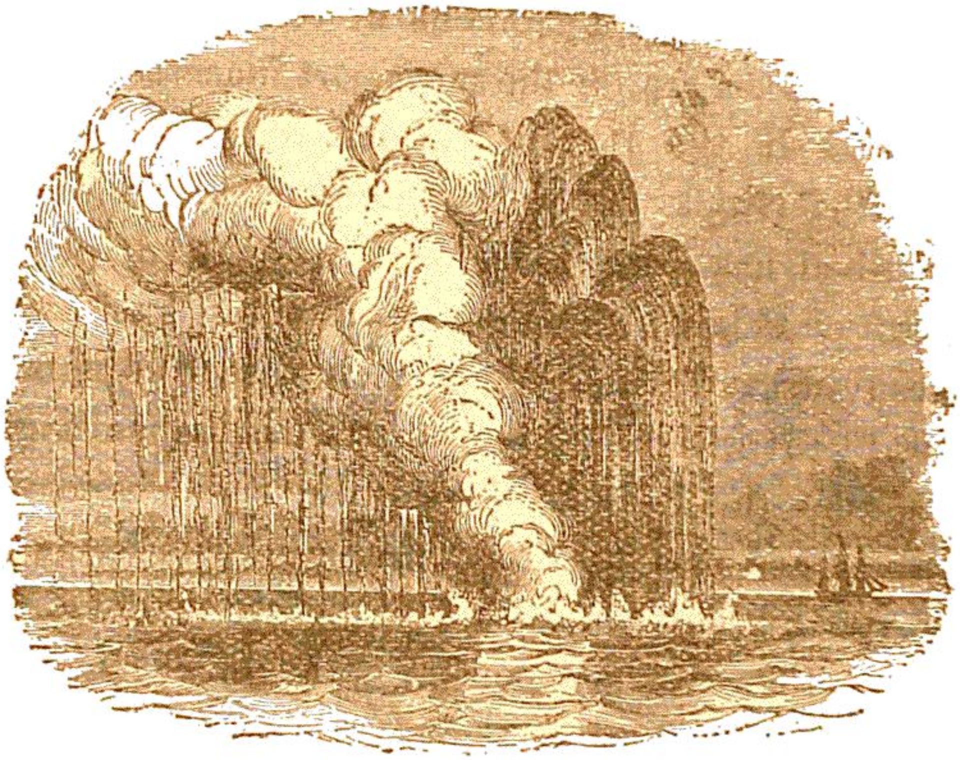

Fig. 64.—Sketch of submarine volcanic eruption (Sabrina Island) off St. Michael's, June, 1811.

coast of Africa. It reached an extreme height of 200 feet or more above the sea-level (800 feet above sea-bottom) with a circumference of 3 miles, but on the cessation of the eruptions was attacked by the waves and soon demolished, leaving only a shoal to mark its site.[124] In the year 1811, another island was formed by submarine eruption of

[124] Phil. Trans. 1832. Constant Prévost, Ann. des Sci. Nat. xxiv. Mem. Soc. Geol. France, ii. p. 91. Mercalli's "Vulcani," etc., p. 117. For a recent submarine eruption in the Mediterranean, see Ricco, Compt. Rend. Nov. 23, 1891.

the coast off St. Michael's in the Azores (Fig. 64). Consisting, like the Mediterranean example, of loose cinders, it rose to a height of about 300 feet, with a circumference of about a mile, but subsequently disappeared.[125] In the year 1796 the island of Johanna Bogoslawa, in Alaska, appeared above the water, and in four years had grown into a large volcanic cone, the summit of which was 3,000 feet above sea-level.[126]

Unfortunately, the phenomena of recent volcanic eruptions under the sea are for the most part inaccessible. Here and there, as in the Bay of Naples, at Etna, among the islands of the Greek Archipelago, and at Tahiti, elevation of the sea-bed has taken place, and brought to the surface beds of tuff or of lava, which have consolidated under water. Both Vesuvius and Etna began their career as submarine volcanoes.[127] It will be seen from the accompanying chart (Fig. 65), that the Islands of Santorin and Therasia form the unsubmerged portions of a great crater-rim rising round a crater which descends 1278 feet below sea-level. The materials of these islands consist of a nucleus of marbles and schists nearly buried under a pile of tuffs (trass), scoriæ, and sheets of lava, the bedded character of which is well shown in the accompanying sketch by Admiral Spratt (Fig. 66), who, with the late Prof. Edward Forbes, examined the geology of this interesting district in 1841. They found some of the tuffs to contain marine shells, and thus to bear witness to an elevation of the sea-floor since volcanic action began. More recently the islands have been carefully studied by various observers. K. von Fritsch has

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125 De la Beche, "Geological Observer," p. 70.

126 D. Forbes, Geol. Mag. vii. p. 323.

127 See, as regards Etna, "Der Aetna," ii. p. 327.

found recent marine shells in many places up to heights of nearly 600 feet above the sea. The strata containing these remains he estimates to be at least 100 to 120 metres thick, and he remarks that in every case he found them to consist essentially of volcanic debris

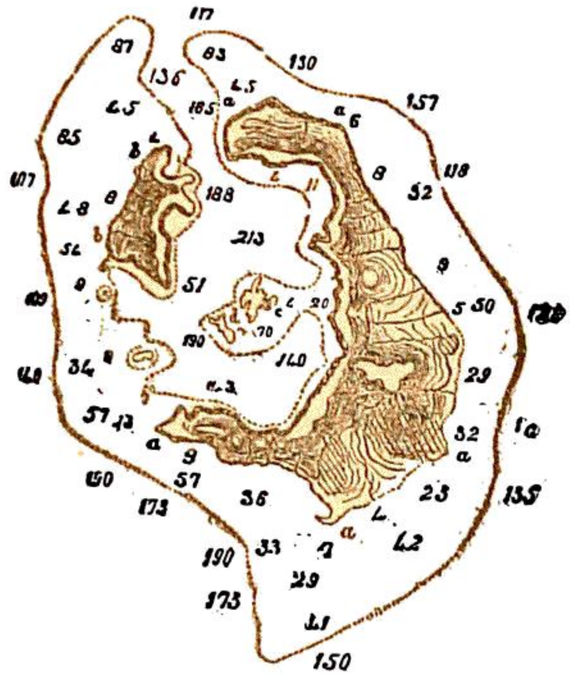

Fig. 65.—Map of partially-submerged volcano of Santorin.

a, Thera, or Santorin; *b*, Therasia; *c*, Mikro Kaimeni; *d*, Neo Kaimeni. The figures denote soundings in fathoms, the dotted line marks the 100 fathoms line.

and to rest upon volcanic rocks. It is evident, therefore, that these shell-bearing tuffs were originally deposited on the sea-floor after volcanic action had begun here, and that during later times they were

Fig. 66.—View of the interior of the crater of Santorin from the entrance.

a, Town of Apanomeria, standing on tuffs, etc.; *b*, Northwest cape of Santorin, with bedded tuffs and lavas; *c*, Mount St. Elias (568 metres), consisting of marble, etc. (shown by oblique lines in the chart, Fig. 65) and forming with the surrounding district a non-volcanic tract in the midst of the lavas and tuffs; *d*, Mikro Kaimeni; *e*, Neo Kaimeni, the scene of the eruptions in 1866-67; *f*, Therasia, an island composed, like Santorin, of beds of tuff, slags and lavas.

upraised, together with the submarine lavas associated with them.[128] Fouqué concludes that the volcano formed at one time a large island with wooded slopes and a somewhat civilized human population, cultivating a fertile valley in the southwestern district, and that in prehistoric times the tremendous explosion occurred whereby the centre of the island was blown out.

The similarity of the structure of Santorin to that of Somma and Etna is obvious. Volcanic action still continues there, though on a diminished scale. In 1866–67 an eruption took place on Neo Kaimeni, one of the later-formed islets in the centre of the old crater, and greatly added to its area and height. The recent eruptions of Santorin, which have been studied in great detail, are specially interesting from the additional information they have supplied as to the nature of volcanic vapors and gases. Among these, as already stated (p. 334), free hydrogen plays an important part, constituting, at the focus of discharge, thirty per cent of the whole. By their eruption under water, the mingling of these gases with atmospheric air and the combustion of the inflammable compounds is there prevented, so that the gaseous discharges can be collected and analyzed. Probably were operations of this kind more practicable at terrestrial volcanoes, free hydrogen and its compounds would be more abundantly detected than has hitherto been possible.

The numerous volcanoes which dot the Pacific Ocean,

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[128] See Fritsch, Z. Deutsch. Geol. Ges. xxiii. (1871), pp. 125–213. The most complete and elaborate work is Fouqué's monograph (already cited), "Santorin et ses Eruptions," Paris, 4to, 1880, where copious analyses of rocks, minerals and gaseous emanations, with maps and numerous admirable views and sections, are given. In this volume a bibliography of the locality will be found. Compare C. Doelter on the Ponza Islands, Denksch. Akad. Wissensch. Vienna, xxxvi. p. 141. Sitz. Akad. Wissensch. Vienna, lxxi. (1875), p. 49.

probably in most cases began their career as submarine vents, their eventual appearance as subaerial cones being mainly due to the accumulation of erupted material, but also partially, as in the case of Santorin, to actual upheaval of the sea-bottom. The lonely island of St. Paul (Figs. 67 and 69), lying in the Indian Ocean more than 2000 miles from the nearest land is a notable example of the summit of a volcanic mountain rising to the sea-level in mid-ocean. Its circular crater, broken down on the northeast side, is filled with water having a depth of 30 fathoms.[129]

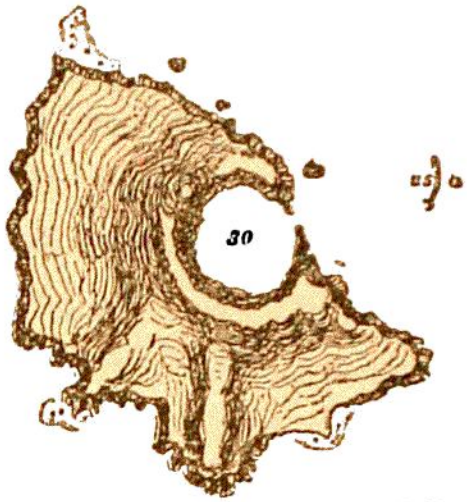

Fig. 67.—Volcanic crater of St. Paul Island, Indian Ocean.

Observations by R. von Drasche have shown that at Bourbon (Réunion), during the early submarine eruptions of that volcano, coarsely crystalline rocks (gabbro) were emitted, that these were succeeded by andesitic and trachytic lavas: but that when the vent rose above the sea, basalts were poured out.[130] Fouqué observes that at Santorin some of the early submarine lavas are identical with those of later subaerial origin, but that the greater part of

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[129] For a general account of the volcanic islands of the ocean, see Darwin's "Volcanic Islands," 2d edit. 1876. For the Philippine volcanoes, see R. von Drasche, Tschermak's Mineralogische Mittheil. 1876; Semper's "Die Philippinen und ihre Bewohner," Würzburg, 1869. For the Kurile Islands, J. Milne, Geol. Mag. 1879, 1880, 1881; Volcanoes of Bay of Bengal (Barren Island, etc.), V. Ball, Geol. Mag. 1879, p. 16; 1888, p. 404; F. R. Mallet, Mem. Geol. Surv. India, xxi. part iv. St. Paul (Indian Ocean), C. Vélain, Assoc. Fran. 1875, p. 581; "Mission à l'ile St. Paul," 1879; "Description geologique de la Presqu'ile d'Aden," etc., 4to, Paris, 1878; and "Les Volcans," 1884. For Isle of Bourbon, see authorities cited on p. 415, and for Hawaii, the references on p. 350.

[130] Tschermak's Mineralogische Mittheil. 1876, pp. 42, 157. A similar structure occurs at Palma (Cohen, Neues Jahrb. 1879, p. 482) and in St. Paul (Vélain as above cited).

them belong to an entirely different series, being acid rocks, belonging to the group of hornblende-andesites, while the subaerial rocks are augite-andesites. The acidity of these lavas has been largely increased by the infusion into them of much silica, chiefly in the form of opal. They differ much in aspect, being sometimes compact, scoriaceous, hard, like millstone, with perlitic and spherulitic structures, while they frequently present the characters of trass impregnated with opal and zeolites. Among the fragmental ejections there occur blocks of schist and granitoid rocks, probably representing the materials below the sea-floor through which the first explosion took place (pp. 341, 363, 417). During the eruption of 1866 some islets of lava rose above the sea in the middle of the bay, near the active vent. The rock in these cases was compact, vitreous, and much cracked.'[131]

Among submarine volcanic formations, the tuffs differ from those laid down on land chiefly in their organic contents; but partly also in their more distinct and originally less inclined bedding, and in their tendency to the admixture of non-volcanic or ordinary mechanical sediment with the volcanic dust and stones. No appreciable difference either in external aspect or in internal structure seems yet to have been established between subaerial and submarine lavas. Some undoubtedly submarine lavas are highly scoriaceous. There is no reason, indeed, why slaggy lava and loose, non-buoyant scoriæ should not accumulate under the pressure of a deep column of the ocean. At the Hawaii Islands, on 25th February, 1877, masses of pumice, during a submarine volcanic explosion, were

[131] Fouqué, "Santorin."

ejected to the surface, one of which struck the bottom of a boat with considerable violence and then floated. When we reflect, indeed, to what a considerable extent the bottom of the great ocean-basins is dotted over with volcanic cones, rising often solitary from profound depths, we can believe that a large proportion of the actual eruptions in oceanic areas may take place under the sea. The immense abundance and wide diffusion of volcanic detritus (including blocks of pumice) over the bottom of the Pacific

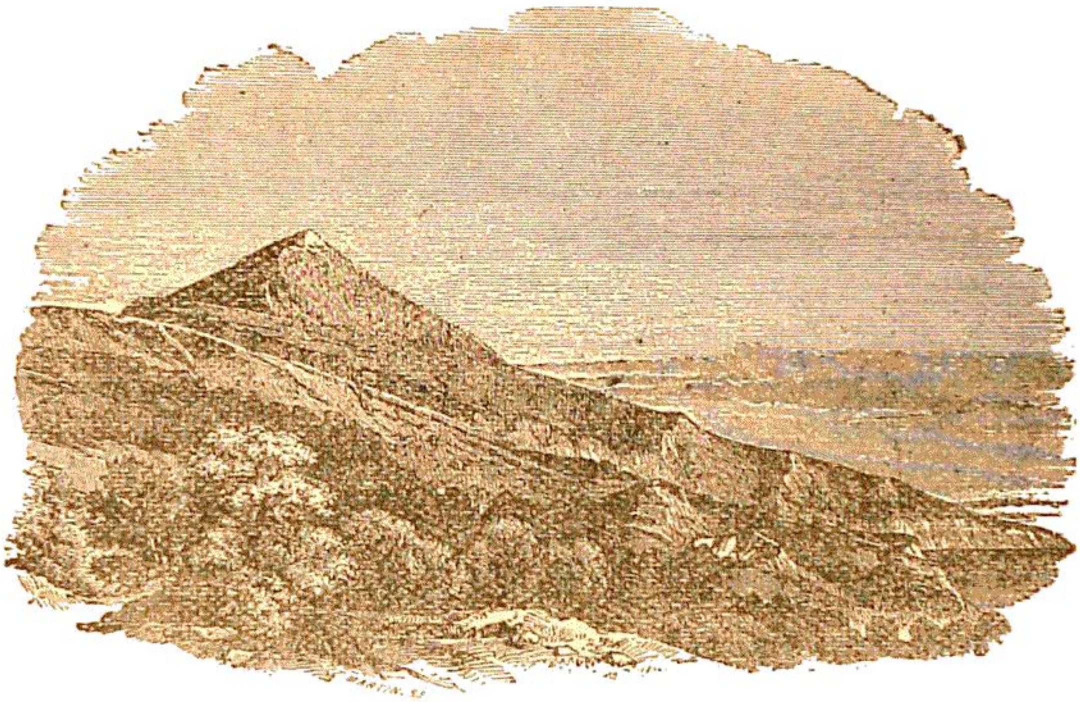

Fig. 68.—View of the Peak of Teneriffe and its coast-erosion.

and Atlantic oceans, even at distances remote from land, as made known by the voyage of the "Challenger," doubtless indicate the prevalence and persistence of submarine volcanic action, even though, at the same time, an extensive diffusion of volcanic débris from the islands is admitted to be effected by winds and ocean-currents.

Volcanic islands, unless continually augmented by renewed eruptions, are attacked by the waves and cut down. Graham's Island and the other examples above cited show

how rapid this disappearance may be. The island of Volcano has the base of its slopes truncated by a line of cliff due to marine erosion. The island of Teneriffe shows, in the same way, that the sea is cutting back the land toward the great cone (Fig. 68). The island of St. Paul (Figs. 67, 69) brings before us in a more impressive way the tendency

Fig. 69.—View of St. Paul Island, Indian Ocean, from the east (Capt. Blackwood in Admiralty Chart).

a, Nine-pin Rock, a stack of harder rock left by the sea; *b*, entrance to crater lagoon (see Fig. 67); *c*, *d*, *e*, cliffs composed of bedded volcanic materials dipping toward the south, and much eroded at the higher end (*c*) by waves and subaerial waste; *f*, southern point of the island, likewise cut away into a cliff.

of volcanic islands to be destroyed unless replenished by continual additions to their surface. At St. Helena lofty cliffs of volcanic rocks 1000 to 2000 feet high bear witness to the enormous denudation whereby masses of basalt two or three miles long, one or two miles broad, and 1000 to 2000 feet thick, have been entirely removed.[132]

ii. *Fissure* (*Massive*) *Eruptions*

Under the head of massive or homogeneous volcanoes some geologists have included a great number of bosses or dome-like projections of once-melted rock which, in regions of extinct volcanoes, rise conspicuously above the surface without any visible trace of cones or craters of fragmentary material. They are usually regarded as protrusions of lava, which, like the Puy de Dôme in Auvergne, assumed a dome-form at the surface without spreading out in sheets

[132] Darwin, "Volcanic Islands," p. 104. For a more detailed account of this island, see J. C. Melliss' "St. Helena," London, 1875.

over the surrounding country, and with no accompanying fragmentary discharges. But the mere absence of ashes and scoriæ is no proof that these did not once exist, or that the present knob or boss of lava may not originally have solidified within a cone of tuff which has been subsequently removed in denudation. The extent to which the surface of the ground has been changed by ordinary atmospheric waste, and the comparative ease with which loose volcanic dust and cinders might have been entirely removed, require to be considered. Hence, though the ordinary explanation is no doubt in some cases correct, it may be doubted whether a large proportion of the examples cited from the Rhine, Bohemia, Hungary, and other regions, ought not rather to be regarded, like the "necks" so abundant in the ancient volcanic districts of Britain (Book IV. Part VII.), as the remaining roots of ordinary volcanic cones. If the tuff of a cone, up the funnel of which lava rose and solidified, were swept away, we should find a central lava plug or core resembling the volcanic "heads" (*vulkanische Kuppen*) of Germany. Unquestionably, lava has in innumerable instances risen in this way within cones of tuff or cinders, partially filling them without flowing out into the surrounding country.[183]

But while, on either explanation of their origin, these volcanic "heads" find their analogues in the emissions of lava in modern volcanoes, there are numerous cases in old volcanic areas where the eruptions, so far as can now be judged, were not attended with the production of any central cone or crater. Such emissions of lava may have

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183 Von Seebach, Z. Deutsch. Geol. Ges. xviii. p. 643. F. von Hochstetter, Neues Jahrb. 1871, p. 469. Reyer, Jahrb. K. K. Geol. Reichsanstalt, 1878, p. 81; 1879, p. 463.

resembled those which in recent times have occurred at the Hawaiian volcanoes, where enormous accumulations of lava have gradually been built up into flat domes, of which Mauna Loa rises to a height of 13,675 feet. Vast floods of remarkably liquid basic lava have from time to time flowed out tranquilly without explosion or earthquake, and with no accompaniment of fragmental discharges. These currents of molten rock have spread out into wide sheets, sloping at so low an angle that they look horizontal. The lower and older portions of them have been eroded by streams so as to present escarpments and outliers not unlike those of western North America or the older basaltic plateaus of Britain and India.[134]

The most stupendous modern basaltic-floods of Iceland issued from vents along a fissure. According to Thoroddsen the post-glacial lava-fields of Odadahraun, covering an area of about 4390 square kilometres, have issued from about 20 distinct vents, while in the east of Iceland the lava has flowed from the lips of fissures.[135] It would seem that for the discharge of such wide and flat sheets of lava, great mobility and tolerably complete fusion of the molten mass is necessary. The phenomenon occurs among the more basic lavas (basalts, etc.) rather than among the more lithoid acid lavas (trachytes, rhyolites, etc.).

In former geological ages, extensive eruptions of lava, without the accompaniment of scoriæ, with hardly any fragmentary materials, and with, at the most, only flat

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[134] For a graphic account of the Hawaiian lava-fields, see Captain Dutton, Fourth Annual Report, U. S. Geol. Survey for 1882–83. See also Dana's "Characteristics of Volcanoes."

[135] See W. L. Watts' "Across the Vatna Jökull," Proc. Roy. Geog. Soc. 1876. W. G. Lock, Geol. Mag. 1881, p. 212; and papers by Thoroddsen and Holland, quoted ante, p. 345.

dome-shaped cones at the points of emission, have taken place over wide areas from scattered vents, along lines or systems of fissures. Vast sheets of lava have in this manner been poured out to a depth of many hundred feet, completely burying the previous surface of the land and forming wide plains or plateaus. These truly "massive eruptions" have been held by Richthofen[136] and others to represent the grand fundamental character of volcanism, ordinary volcanic cones being regarded merely as parasitic excrescences on the subterranean lava-reservoirs, very much in the relation of minor cinder cones to their parent volcano.[137]

Though a description of these old fissure or massive eruptions ought properly to be included in Book IV., the subject is so closely connected with the dynamics of existing active volcanoes that an account of the subject may be given here. Perhaps the most stupendous example of this type of volcanic structure occurs in Western North America. The extent of country which has been flooded with basalt in Oregon, Washington, California, Idaho, and Montana has not yet been accurately surveyed, but has been estimated to cover a larger area than France and Great Britain combined, with a thickness averaging 2000 but reaching in some places to 3700 feet.[138] The Snake River plain in Idaho (Fig. 70) forms part of this lava-flood. Surrounded on the north and east by lofty mountains, it stretches westward as an apparently boundless desert of sand and bare sheets of black basalt. A few streams descending into the plain from the hills are soon swallowed up and lost. The Snake River, however, flows across it, and has cut out of its lava-beds a

[136] Trans. Akad. Sci. California, 1868.
[137] Proc. Roy. Phys. Soc. Edin. v. 236; Nature, xxiii. p. 3.
[138] J. LeConte. Amer. Journ. Sci. 3d ser. vii. (1874), 167, 259.

series of picturesque gorges and rapids. Looked at from any point on its surface, it appears as a vast level plain like that of a lake-bottom, though more detailed examination may detect a slope in one or more directions, and may thereby obtain evidence as to the sites of the chief openings from which the basalt was poured forth. The uniformity of surface has been produced either by the lava flowing over a plain or lake-bottom, or by the complete effacement of an original and undulating contour of the ground under

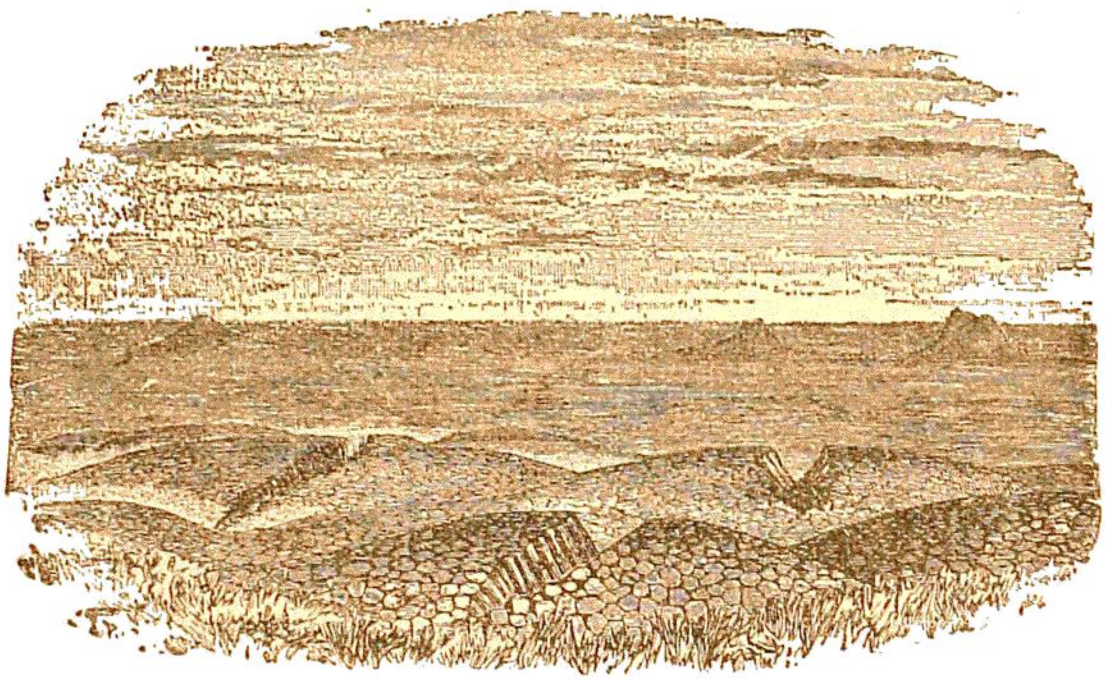

Fig. 70.—View of the great Basalt-plain of the Snake River, Idaho, with recent cones.

hundreds of feet of volcanic rock in successive sheets. The lava rolling up to the base of the mountains has followed the sinuosities of their margin, as the waters of a lake follow its promontories and bays. The author crossed the Snake River plain in 1879, and likewise rode for many miles along its northern edge. He found the surface to be everywhere marked with low hummocks or ridges of bare black basalt, the surfaces of which exhibited a reticulated pavement of the ends of columns. In some places, there was a perceptible tendency in these ridges to range themselves in one general northeasterly direction, when they might be likened to a series of long, low waves, or ground-swells. In many instances the crest of each ridge had cracked open into a fissure which presented along its walls a series of tolerably symmetrical columns (Fig. 70). That these ridges were original undulations of the lava, and had not been produced by erosion, was indicated by the fact that the columns were perpendicular to their surface, and changed in direction according to the form of the ground which was the original cooling surface of the lava. Though the basalt was sometimes vesicular, no layers of slag or scoriæ were anywhere observed, nor did the surfaces of the ridges exhibit any specially scoriform character.

There are no great cones whence this enormous flood of basalt could have flowed. It probably escaped from orifices or fissures still concealed under the sheets which issued from them, the points of escape being marked only by such low domes as could readily be buried under the succeeding eruptions from other vents.[139] That it was not the result of one sudden outpouring of rock is shown by the distinct bedding of the basalt, which is well marked along the river ravines. It arose from what may have been, on the whole, a continuous though locally intermittent welling-out of lava, probably from vents on many fissures extending over a wide tract of Western America during a late Tertiary period, if, indeed, the eruptions did not partly come within the time of the human occupation of the continent. The discharge of lava continued until the previous topography was buried under some 2000 feet of lava, only the higher

[139] Captain Dutton has remarked the absence of any conspicuous feature at the sources from which some of the largest lava-streams of Hawaii have issued.

summits still projecting above the volcanic flood.[140] At a few points on the plain and on its northern margin, the author observed some small cinder cones (Fig. 70). These were evidently formed during the closing stages of volcanic action, and may be compared to the minor cones on a modern volcano, or better, to those on the surface of a recent lava-stream.

In Europe, during older Tertiary time, similar enormous outpourings of basalt covered many hundreds of square miles. The most important of these is that which occupies a large part of the northeast of Ireland, and in disconnected areas extends through the Inner Hebrides and the Faroe Islands into Iceland. Throughout that region, the paucity of evidence of volcanic vents is truly remarkable. So extensive has been the denudation, that the inner structure of the volcanic plateaus has been admirably revealed. The ground beneath and around the basalt-sheets has been rent into innumerable fissures which have been filled by the rise of basalt into them. A vast number of basalt-dikes ranges from the volcanic area eastward across Scotland and the north of England and the north of Ireland. Toward the west the molten rock reached the surface and was poured out there, while to the eastward it does not appear to have overflowed, or, at least, all evidence of the outflow has been removed in denudation. When we reflect that this system of dikes can be traced from the Orkney Islands southward into Yorkshire and across Britain from sea to sea, over a total area of probably not less than 100,000 square miles, we can in some measure appreciate the volume of molten basalt which in older Tertiary times underlay large tracts of

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[140] Prof. J. LeConte believes that the chief fissures opened in the Cascade and Blue Mountain Ranges. Amer. Journ. Sci. 3d series, v. (1874) p. 168.

the site of the British Islands, rose up in so many thousands of fissures, and poured forth at the surface over so wide an area in the northwest.[141]

In Africa, basaltic plateaus cover large tracts of Abyssinia, where by the denuding effect of heavy rains they have been carved into picturesque hills, valleys, and ravines.[142] In India, an area of at least 200,000 square miles is covered by the singularly horizontal volcanic plateaus of the "Deccan Traps" (lavas and tuffs), which belong to the Cretaceous period and attain a thickness of 6000 feet or more.[143] The underlying platform of older rock, where it emerges from beneath the edges of the basalt table-land, is found to be in many places traversed by dikes; but no cones and craters are anywhere visible. In these, and probably in many other examples still undescribed, the formation of great plains or plateaus of level sheets of lava is to be explained by "fissure-eruptions" rather than by the operations of volcanoes of the familiar "cone and crater" type.

§ 4. Geographical and geological distribution of volcanoes

Adequately to trace the distribution of volcanic action over the globe, account ought to be taken of dormant and extinct volcanoes, likewise of the proofs of volcanic outbreaks during earlier geological periods. When this is done, we learn, on the one hand, that innumerable districts have been the scene of prolonged volcanic activity, where there is now no underground commotion, and on the other, that volcanic outbursts have been apt to take place

141 Trans. Roy. Soc. Edin. xxxv. (1888), p. 21.
142 Blanford's "Abyssinia," 1870, p. 181.
143 Medlicott and Blanford, "Geology of India," p. 299.

again and again after wide intervals on the same ground, some modern active volcanoes being thus the descendants and representatives of older ones. Some of the facts regarding former volcanic action have been already stated. Others will be given in Book IV. Part VII.

Confining attention to vents now active, of which the total number may be about 300,[144] the chief facts regarding their distribution over the globe may be thus summarized. (1) Volcanoes occur along the margins of the ocean-basins, particularly along lines of dominant mountain-ranges, which either form part of the mainland of the continents or extend as adjacent lines of islands. The vast hollow of the Pacific is girdled with a wide ring of volcanic foci. (2) Volcanoes rise, as a striking feature, from the submarine ridges that traverse the ocean basins. All the oceanic islands are either volcanic or formed of coral, and the scattered coral-islands have in all likelihood been built upon the tops of submarine volcanic cones. (3) Volcanoes are situated not far from the sea. The only exceptions to this rule are certain vents in Mantchuria and in the tract lying between Thibet and Siberia; but of the actual nature of these vents very little is yet known. (4) The dominant arrangement of volcanoes is in series along subterranean lines of weakness, as in the chain of the Andes, the Aleutian Islands, and the Malay Archipelago. A remarkable zone of volcanic vents girdles the globe from Central America eastward by the Azores and Canary Islands to the Mediterranean, thence to the Red Sea,

[144] This number is probably below the truth. Prof. J. Milne has enumerated in Japan alone no fewer than fifty-three volcanoes which are either active or have been active within a recent period. He remarks that, "if we were in a position to indicate the volcanoes which had been in eruption during the last 4,000 years, the probability is that they would number several thousands rather than four or five hundred." "Earthquakes and other Earth-movements," 1886, p. 227. Compare Fisher, "Physics of Earth's Crust," 2d ed. chap. xxiv.

and through the chains of islands from the south of Asia to New Zealand and the heart of the Pacific. (5) On a smaller scale the linear arrangement gives place to one in groups, as in Italy, Iceland, and the volcanic islands of the great oceans.

In the European area there are six active volcanoes—Vesuvius, Etna, Stromboli, Volcano, Santorin, and Nisyros. Asia contains twenty-four, Africa ten, North America twenty,[145] Central America twenty-five, and South America thirty-seven.[146] By much the larger number, however, occur on islands in the ocean. In the Arctic Ocean rises the solitary Jan Mayen. On the ridge separating the Arctic and Atlantic basins, the group of Icelandic volcanoes is found. Along the great central ridge of the Atlantic bottom, numerous volcanic vents have risen above the surface of the sea—the Azores, Canary Islands, and the extinct degraded volcanoes of St. Helena, Ascension and Tristan d'Acunha. On the eastern border lie the volcanic vents of the islands off the African coast, and to the west those of the West India Islands. Still more remarkable is the development of volcanic energy in the Pacific area. From the Aleutian Islands southward, a long line of volcanoes, numbering upward of a hundred active vents, extends through Kamtschatka and the Kurile Islands to Japan,[147] whence

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[145] For an account of the remarkable extinct volcanoes of Northern California, Oregon and Washington Territory, see A. Hague and J. P. Iddings. Amer. Journ. Sci. xxvi. (1883), p. 222. On Volcanoes of Mexico see H. Lenk, "Beiträge zur Geologie und Palæontologie der Republik Mexico," Leipzig, 1890; of Central America, A. Dolfuss and E. de Monserrat, "Voyage Geologique," Paris, folio, 1868; K. von Seeback, Abh. Kön. Ges. Wiss. Göttingen, xxxviii. (1892).

[146] For a recent account of the volcanoes of the Andes of the Equator see Whymper's "Travels amongst the Great Andes."

[147] For the volcanoes of Japan, besides papers quoted on p. 364, see W. J. Holland, Appalachia, vi. (1890), 109. E. Naumann, Zeitsch. Deutsch. Geol. Ges. 1877, p. 364. Mr. Milne enumerates 100 active vents from the Kuriles to Kinshu (2,000 miles).

another numerous series carries the volcanic band far south toward the Malay Archipelago, which must be regarded as the chief centre of the present volcanic activity of our planet. In Sumatra, Java, and adjoining islands, no fewer than fifty active vents occur. The chain is continued through New Guinea and the groups of islands to New Zealand.[148] Even in the Antarctic regions, Mounts Erebus and Terror are cited as active vents; while in the centre of the Pacific Ocean rise the great lava cones of the Sandwich Islands. In the Indian Ocean, the Red Sea, and off the east coast of Africa a few scattered vents appear.

Besides the existence of extinct volcanoes which have obviously been active in comparatively recent times, the geologist can adduce proofs of the former presence of active volcanoes in many countries where cones, craters, and all the ordinary aspects of volcanic mountains, have long disappeared, but where sheets of lava, beds of tuff, dikes, and necks representing the sites of volcanic vents have been recognized abundantly (Book IV. Part VII.). These manifestations of volcanic action, moreover, have as wide a range in geological time as they have in geographical area. Every great geological period, back into pre-Cambrian time, seems to have had its volcanoes. In Britain, for instance, there were probably active volcanic vents in pre-Cambrian ages. The Archæan gneiss of N. W. Scotland includes a remarkable series of dikes presenting some points of resemblance to the great Tertiary system. The Torridon sandstone of the same region, which is now known to be pre-Cambrian,

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[148] The great eruption of Tarawera, New Zealand, in 1886, is described by Prof. A. P. W. Thomas, "Report on the Eruption of Tarawera," published by the Government in 1888: also Prof. Hutton's "Report on the Tarawera Volcanic District, Wellington, 1887," Quart. Journ. Geol. Soc. xliii. (1887), p. 178.

contains pebbles of various finely vesicular porphyrites, and in one place includes a band of true tuff. In the lower Cambrian period the tuffs and diabases of Pembrokeshire were erupted. Still more vigorous were the volcanoes in the Lower Silurian period, when the lavas and tuffs of Snowdon, Aran Mowddwy, and Cader Idris were ejected. During the deposition of the Upper Silurian rocks a few volcanoes were active in the west of Ireland. The Lower Old Red Sandstone epoch was one of prolonged activity in central Scotland. The earlier half of the Carboniferous period likewise witnessed two distinct epochs of volcanic activity over the same region. In the earlier of those, lavas (andesites and trachytes) were poured out in wide level plateaus from many vents, while in the later, groups of minor cones like the puys of Auvergne were dispersed among the lagoons. During Permian time, more than a hundred small vents rose in scattered groups across the centre and southwest of Scotland, while a few similar points of eruption appeared in the southwest of England. No trace of any British Mesozoic volcanoes has been met with. The vast interval between Permian and older Tertiary time appears to have been a period of total quiescence of volcanic activity. The older Tertiary ages were distinguished by the outpouring of the enormous basaltic plateaus of Antrim and the Inner Hebrides.[149]

In France and Germany, likewise, Palæozoic time was marked by the eruption of many diabase, porphyrite, and quartz-porphyry lavas. In Brittany, for example, Dr. Barrois has found a remarkable series of older Palæozoic dia-

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[149] For a detailed summary of the volcanic history of Britain, see Presidential addresses to the Geological Society, Quart. Journ. Geol. Soc. xlvii., xlviii. (1891–92).

bases and porphyrites with tuffs and agglomerates. He distinguishes four principal periods of eruption—1. Cambrian and Lower Silurian; 2. Middle and Upper Silurian; 3. Upper Devonian; 4. Carboniferous.[150] The Permian period was marked in Germany and also in the south of France by the discharge of great masses of various quartz-porphyries. The Triassic period likewise witnessed numerous eruptions. But from that period onward the same remarkable quiescence appears to have reigned all over Europe which characterized the geological history of Britain during Mesozoic time.[151] In Tertiary time a prodigious outpouring of lavas, both acid and basic, continued from the Miocene epoch down even perhaps to the historic period. Examples of this great series are met with in Central France, the Eifel, Italy,[152] Bohemia, and Hungary, almost to the existing period.[153] Recent research has brought to light evidence of a long succession of Tertiary and post-Tertiary volcanic outbursts in Western America (Nevada, Oregon, Idaho, Utah, etc.). Contemporaneous volcanic rocks are associated with Palæozoic, Secondary, and Tertiary formations in New Zealand, and volcanic action there is not yet extinct.

Thus it can be shown that, within the same comparatively limited geographical space, volcanic action has been

[150] Carte Geol. detaill. France, No. 7, 1889.

[151] Some trifling exceptions to this general statement are said to occur. C. E. M. Rohrbach describes Cretaceous teschenites and diabases in Silesia (Tschermak's Min. Mittheil. vii. (1885, p. 15). P. Choffat refers to Cenomanian eruptions in Portugal (Journ. Sciencias Math. Phys. Natur, Lisbon, 1884). A. E. Lagorio has found in the Crimea a series of sheets, dikes and bosses, ranging from nevadites to basalts.

[152] For early and classical accounts of the Italian volcanic districts, see Spallanzani's "Voyages dans les deux Siciles," and Breislak's "Voyages Physiques et Lythologiques dans la Campanie." Consult also Mercalli's "Vulcani," etc., and Johnston-Lavis' "South Italian Volcanoes," already cited.

[153] For a recent attempt to give a stratigraphical and geographical view of the distribution of igneous rocks in Europe, see M. Bertrand, Bull. Soc. Geol. France, xvi. (1888), p. 573.

rife at intervals during a long succession of geological ages. Even round the sites of still active vents, traces of far older eruptions may be detected, as in the case of the existing active volcanoes of Iceland, which rise from amid Tertiary lavas and tuffs. Volcanic action, which now manifests itself so conspicuously along certain lines, seems to have continued in that linear development for protracted periods of time. The actual vents have changed, dying in one place and breaking out in another, yet keeping on the whole along the same tracts. Taking all the manifestations of volcanic action together, both modern and ancient, we see that the subterranean forces have operated along great lines in the earth's crust, and that the existing volcanoes form but a small proportion of the total number of once active vents.

Looking broadly at the geological history of volcanic action we observe that, while there is evidence of the protrusion of both acid and basic materials from the remotest periods, the earlier discharges were preponderantly acid. In Britain, for example, the vast piles of lavas ejected during the Silurian period were mainly of a felsitic character, though considerable accumulations of andesites were not wanting. On the other hand, the wide sheets of lava poured out in this country during Tertiary time were chiefly basalts, the acid protrusions occurring mostly as dikes and bosses. A similar broad sequence has been observed in other countries.

When, however, we proceed to consider more closely the nature of the successive eruptions during the continuance of one of the volcanic periods of which records are preserved among the geological formations, we discover proofs of a remarkable variation in the character of the lavas.[154] Various

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[154] In some volcanoes (*e.g.* Teneriffe) the lower lavas are heavier and more basic than the upper.

observers have noticed that volcanic rocks have succeeded each other in a certain order in different regions. Baron von Richthofen deduced from observations in Europe and America a general sequence of volcanic succession, which he arranged in the following order: 1. Propylite; 2. Andesite; 3. Trachyte; 4. Rhyolite; 5. Basalt.[155] This sequence he believed to be seldom or never complete in any one locality; sometimes only one member of the series may be found; but when two or more occur they follow, in his opinion, this sequence, basalt being everywhere the latest of the series. The subject has been more recently discussed by M. Bertrand, who remarks that in Europe each of the great areas of plication has given rise to the formation of eruptive rocks of every composition and structure. He recognizes a recurrence of the phenomena in successive geological periods, and speaks of a definite order of eruptions in the same series.[156]

The great volcanic series of Auvergne presents a marvellous succession of varied eruptions within a limited region during what was probably a single volcanic period. The first eruptions appear to have been basalts, and rocks of similar character reappeared again and again in later stages of the history, the intervening eruptions consisting of phonolites, trachytes, rhyolites, or andesites. The latest lavas were scoriaceous basalts.[157] Among the later Palæozoic volcanic eruptions of Britain a more definite and regular recurrence of rocks appears to be traceable. The earlier lavas of the Old Red Sandstone and Carboniferous series were generally either intermediate or basic, sometimes remarkably basic, while the late protrusions were decidedly acid. At

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155 "The Natural System of Volcanic Rocks," Californ. Acad. Sci. 1868.
156 Bull. Soc. Geol. France, xvi. (1888), p. 611.
157 Carte Geol. detaill. France, Feuille 166 (Clermont Ferrand).

the one end we find basalts or diabases and picrites, followed sometimes by copious outpourings of andesites, while at the other end come intrusions of felsites and quartz-porphyries. Again, among the Tertiary lavas, the basalts of the great plateaus are pierced by bosses and dikes of granophyre and allied acid rocks. In these various examples the facts point to some gradual change in the composition of the subterranean magma during the lapse of a single volcanic period—a change in which there was a separation of basic constituents and the discharge of more basic lavas, leaving a more acid residuum to be erupted toward the end of the activity.[158]

§ 5. Causes of Volcanic Action

The *modus operandi* whereby the internal heat of the globe manifests itself in volcanic action is a problem to which as yet no satisfactory solution has been found. Were this action merely an expression of the intensity of the heat, we might expect it to have manifested itself in a far more powerful manner in former periods, and to exhibit a regularity and continuity commensurate with the exceedingly slow diminution of the earth's temperature. But there is no geological evidence in favor of greater volcanic intensity in ancient than in more recent periods; on the contrary, it may be doubted whether any of the Palæozoic volcanoes equalled in magnitude those of Tertiary and perhaps even post-Tertiary times. On the other hand, no feature of volcanic action is more conspicuous than its spasmodic fitfulness.[159]

As physical considerations negative the idea of a com-

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[158] Quart. Journ. Geol. Soc. vol. xlviii. (1892), p. 177.

[159] Consult Dana, "Characteristics of Volcanoes," p. 15 *et seq.* Dutton, U. S. Geol. Rep. 1882–83, p. 183 *et seq.* Prestwich, Proc. Roy. Soc. xli. (1886), p. 117. Löwl, Jahrb. Geol. Reichsanst. 1886, p. 315.

paratively thin crust, surmounting a molten interior whence volcanic energy might be derived (*ante*, p. 100), geologists have found themselves involved in great perplexity to explain volcanic phenomena, for the production of which a source of no great depth would seem to be necessary. Some have supposed the existence of pools or lakes of liquid lava lying beneath the crust, and at an inconsiderable depth from the surface. Others have appealed to the influence of the contraction of the earth's mass, assuming the contraction to be now greater in the outer than in the inner portions, and that the effect of this external contraction must be to squeeze out some of the internal molten matter through weak parts of the crust.[160]

That volcanic action is one of the results of terrestrial contraction can hardly be doubted, though we are still without satisfactory data as to the connection between the cause and the effect. It will be observed that volcanoes occur chiefly in lines along the crests of terrestrial ridges. There is probably, therefore, a connection between the elevation of these ridges and the extravasation of molten rock at the surface. The formation of continents and mountain-chains has already been referred to as probably consequent on the subsidence and readjustment of the cool outer shell of the planet upon the hotter and more rapidly contracting nucleus. Every such movement, by relieving pressure on regions below the axis of elevation, will tend to bring up molten rock nearer the surface, and thus to promote the formation and continued activity of volcanoes.

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[160] Cordier, for example, calculated that a contraction of only a single millimetre (about 1-25th of an inch) would suffice to force out to the surface lava enough for 500 eruptions, allowing 1 cubic kilometre (about 1300 million cubic yards) for each eruption. Prof. Prestwich invokes a slight contraction of the crust as the initial cause of volcanic action. Brit. Assoc. 1881, Sects. p. 610.

The fissure-eruptions, wherein lava has risen in innumerable rents in the ground across the whole breadth of a country, and has been poured out at the surface over areas of many thousand square miles, flooding them sometimes to a depth of several thousand feet, undoubtedly prove that molten rock existed at some depth over a large extent of territory, and that, by some means still unknown, it was forced out to the surface (*ante*, p. 434). In investigating this subject, it would be important to discover whether any evidence of great terrestrial crumpling or other movement of the crust can be ascertained to have taken place about the same geological period as a stupendous outpouring of lava—whether, for example, the great lava-fields of Idaho may have had any connection with contemporaneous flexure of the North American mountain-system, or whether the basalt-plateaus of Antrim, Scotland, Faroe, and Iceland may possibly have been in their origin sympathetic with the post-Eocene upheaval of the Alps or other Tertiary movements in Europe. The most striking instance of an apparent connection between such terrestrial disturbances and volcanic phenomena is that supplied by the great semicircle of eruptions that sweeps from Central France by the Eifel, Hochgau, and Bohemia into Hungary, and which has been referred to the dislocations consequent on the upheaval of the Alps.[161]

In the ordinary phase of volcanic action, marked by the copious evolution of steam and the abundant production of dust, slags, and cinders, from one or more local vents, the main proximate cause of volcanic excitement is obvi-

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[161] Suess, "Antlitz der Erde," i. p. 358, pl. iii.; Julien, Annuaire du Club Alpin, 1879–80, p. 446; Michel-Lévy, Bull. Soc. Geol. France, xviii. (1890), pp. 690, 841.

ously the expansive force exerted by vapors dissolved in the molten magma from which lavas proceed. Whether and to what extent these vapors are parts of the aboriginal constitution of the earth's interior, or are derived by descent from the surface, is still an unsolved problem. The abundant occlusion of hydrogen in meteorites, and the capacity of many terrestrial substances, notably melted metals, to absorb large quantities of gases and vapors without chemical combination, and to emit them on cooling with eruptive phenomena, not unlike those of volcanoes, have led some observers to conclude that the gaseous ejections at volcanic vents are portions of the original constitution of the magma of the globe, and that to their escape the activity of volcanic vents is due. Prof. Tschermak in particular has advocated this opinion, and it is meeting with increasing acceptance.[162]

On the other hand, since so large a proportion of the vapor of active volcanoes consists of steam, many geologists have urged that this steam has in great measure been supplied by the descent of water from above ground. The floor of the sea and the beds of rivers and lakes are all leaky. Moreover, during volcanic eruptions and earthquakes, fissures no doubt open under the sea, as they do on land, and allow the oceanic water to find access to the interior.[163] Again, rain sinking beneath the surface of the land, percolates down cracks and joints, and infil-

162 He has suggested that if 190 cubic kilometres, of the constitution of cast-iron, be supposed to solidify annually, and to give off 50 times its volume of gases, it would suffice to maintain 20,000 active volcanoes. Sitz. Akad. Wissen. Wien, lxxv. (1877), p. 151. Reyer ("Beitrag zur Physik der Eruptionen," Vienna, 1877) advocates the same view.

163 Prof. Moseley mentions that during a submarine eruption off Hawaii in 1877 "a fissure opened on the coast of that island, from a few inches to three feet broad, and in some places the water was seen pouring down the opening into the abyss below." "Notes by a Naturalist on the 'Challenger,'" p. 503.

trates through the very pores of the rocks. The presence of nitrogen among the gaseous discharges of volcanoes may indicate the decomposition of water containing atmospheric gases. The abundant sublimations of chlorides are such as might probably result from the decomposition of sea-water. To some extent surface-waters doubtless do reach the volcanic magma.

Whatever may be its source, we cannot doubt that to the enormous expansive force of superheated water (or of its component gases, dissociated by the high temperature), in the molten magma at the roots of volcanoes, the explosions of a crater and the subsequent rise of a lava-column are mainly due. The water or gas dissolved in the lava is retained there by the enormous overlying pressure of the lava-column, but when the molten material is brought up to the surface the pressure is relieved and the water vaporizes and escapes. Where the relief is rapid the effect may be to froth up the lava into a pasty mass of pumice, while where it is sudden and extreme the escape of the water-vapor may be by an explosive discharge.

It has been supposed that, somewhat like the reservoirs in which hot water and steam accumulate under geysers, reservoirs of molten rock receive a constant influx of water from the surface, which cannot escape by other channels, but is absorbed by the internal magma at an enormously high temperature and under vast pressure. In the course of time, the materials filling up the chimney are unable to withstand the upward expansion of this imprisoned vapor or water-substance, so that, after some premonitory rumblings, the whole opposing mass is blown out, and the vapor escapes in the well-known masses of cloud. Meanwhile, the removal of the overlying column relieves the pressure on the lava underneath, saturated with vapors or superheated water. This lava therefore begins to rise in the funnel until it forces its way through some weak part of the cone, or pours over the top of the crater. After a time, the vapor being expended, the energy of the volcano ceases, and there comes a variable period of repose, until a renewal of the same phenomena brings on another eruption. By such successive paroxysms, the forms of the internal reservoirs and tunnels may be changed; new spaces for the accumulation of superheated water being opened, whence in time fresh volcanic vents issue, while the old ones gradually die out.

An obvious objection to this explanation is the difficulty of conceiving that water should descend at all against the expansive force within. But Daubrée's experiments have shown that, owing to capillarity, water may permeate rocks against a high counter-pressure of steam on the further side, and that so long as the water is supplied, whether by minute fissures or through pores of the rocks, it may, under pressure of its own superincumbent column, make its way into highly heated regions.[164] Experience in deep mines, however, rather goes to show that the permeation of water through the pores of rocks gets feebler as we descend.

Reference may be made here to a theory of volcanic action in which the influence of terrestrial contraction as the grand source of volcanic energy was insisted upon by the late Mr. Mallet.[165] He maintained that all the present mani-

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[164] Daubrée, "Geologie Experimentale," p. 274 (criticised adversely by Fisher, "Physics of Earth's Crust," 2d ed. p. 144). Tschermak, cited on page 450. Reyer, "Beitrag zur Physik der Eruptionen," § 1.

[165] Phil. Trans. 1873. See also Daubrée's experimental determination of the quantity of heat evolved by the internal crushing of rocks. "Geologie Experimentale," p. 448. For an adverse criticism of Mallet's view, see Fisher, op. cit. chap. xxii.

festations of hypogene action are due directly to the more rapid contraction of the hotter internal mass of the earth and the consequent crushing in of the outer cooler shell. He pointed to the admitted difficulties in the way of connecting volcanic phenomena with the existence of internal lakes of liquid matter, or of a central ocean of molten rock. Observations made by him, on the effects of the earthquake shocks accompanying the volcanic eruptions of Vesuvius and of Etna, showed that the focus of disturbance could not be more than a few miles deep; that, in relation to the general mass of the globe, it was quite superficial, and could not possibly have lain under a crust of 800 miles or upward in thickness. The occurrence of volcanoes in lines, and especially along some of the great mountain-chains of the planet, was likewise dwelt upon by him as a fact not satisfactorily explicable on any previous hypothesis of volcanic energy. But he contended that all these difficulties disappear when once the simple idea of cooling and contraction is adequately realized. "The secular cooling of the globe," he remarks, "is always going on, though in a very slowly descending ratio. Contraction is therefore constantly providing a store of energy to be expended in crushing parts of the crust, and through that providing for the volcanic heat. But the crushing itself does not take place with uniformity; it necessarily acts *per saltum* after accumulated pressure has reached the necessary amount at a given point, where some of the pressed mass, unequally pressed as we must assume it, gives way, and is succeeded perhaps by a time of repose, or by the transfer of the crushing action elsewhere to some weaker point. Hence, though the magazine of volcanic energy is being constantly and steadily replenished by secular cooling, the effects are intermittent." He offered an experimental proof of the sufficiency of the store of heat produced by this internal crushing to cause all the phenomena of existing volcanoes.[166] The slight comparative depth of the volcanic foci, their linear arrangement, and their occurrence along lines of dominant elevation become, he contended, intelligible under this hypothesis. For since the crushing in of the crust may occur at any depth, the volcanic sources may vary in depth indefinitely; and as the crushing will take place chiefly along lines of weakness in the crust, it is precisely in such lines that crumpled mountain-ridges and volcanic funnels should appear. Moreover, by this explanation its author sought to harmonize the discordant observations regarding variations in the rate of increase of temperature downward within the earth, which have already been cited and referred to unequal conductivity in the crust (p. 97). He pointed out that in some parts of the crust the crushing must be much greater than in other parts; and since the heat "is directly proportionate to the local tangential pressure which produces the crushing and the resistance thereto," it may vary indefinitely up to actual fusion. So long as the crushed rock remains out of reach of a sufficient access of subterranean water, there would, of course, be no disturbance. But if, through the weaker parts, water enough should descend and be absorbed by the intensely hot crushed mass, it would be raised to a very high temperature, and, on sufficient diminution of pressure,

[166] The elaborate and careful experimental researches of this observer will reward attentive perusal. Mallet estimates from experiment the amount of heat given out by the crushing of different rocks (syenite, granite, sandstone, slate, limestone), and concludes that a cubic mile of the crust taken at the mean density would, if crushed into powder, give out heat enough to melt nearly 3¼ cubic miles of similar rock, assuming the melting-point to be 2000° Fahr.

would flash into steam and produce the commotion of a volcanic eruption.

This ingenious theory requires the operation of sudden and violent movements, or at least that the heat generated by the crushing should be more than can be immediately conducted away through the crust. Were the crushing slow and equable, the heat developed by it might be so tranquilly dissipated that the temperature of the crust would not be sensibly affected in the process, or not to such an extent as to cause any appreciable molecular rearrangement of the particles of the rocks. But an amount of internal crushing insufficient to generate volcanic action may have been accompanied by such an elevation of temperature as to induce important changes in the structure of rocks, such as are embraced under the term "metamorphic."

There is, indeed, strong evidence that, among the consequences arising from the secular contraction of the globe, masses of sedimentary strata, many thousands of feet in thickness, have been crumpled and crushed, and that the crumpling has often been accompanied by such an amount of heat and evolution of chemical activity as to produce an interchange and rearrangement of the elements of the rocks—this change sometimes advancing perhaps to the point of actual fusion. (See postea, p. 506, and Book IV. Part VIII.) There is reason to believe that some at least of these periods of intense terrestrial disturbance have been followed by periods of prolonged volcanic action in the disturbed areas. Mr. Mallet's theory is thus, to some extent, supported by independent geological testimony. The existence, however, of large reservoirs of fused rock, at a comparatively small depth beneath the surface, may be conceived as probable, apart from the effects of crushing. The connection of volcanoes with lines of elevation, and consequent weakness in the earth's crust, is what might have been anticipated on the view that the nucleus, though practically solid, is at such a temperature and pressure that any diminution of the pressure, by corrugation of the crust or otherwise, will cause the subjacent portion of the nucleus to melt. Along lines of elevation the pressure is relieved, and consequent melting may take place. On these lines of weakness and fracture, therefore, the conditions for volcanic excitement may be conceived to be best developed, whether arising from the explosive energy of water dissolved in the magma or from water descending to the intensely heated materials underneath the crust. The periodicity of eruptions may thus depend upon the length of time required for the storing up of sufficient steam, and on the amount of resistance in the crust to be overcome. In some volcanoes, the intervals of activity, like those of many geysers, return with considerable regularity. In other cases, the shattering of the crust, or the upwelling of vast masses of lava, or the closing of subterranean passages for the descending water, or other causes may vary the conditions so much, from time to time, that the eruptions follow each other at very unequal periods, and with very discrepant energy. Each great outburst exhausts for a while the vigor of the volcano, and an interval is needed for the renewed accumulation of vapor.

But besides the mechanism by which volcanic eruptions are produced, further problems are presented by the varieties of materials ejected, by the differences which these exhibit at neighboring vents, even sometimes in successive eruptions from the same vent, by the alternation or recurrence of lavas from basic to acid in the continuance of a single volcanic period, and by the repetition of a similar cycle in successive periods. Observations are yet needed from a larger number of ancient volcanic districts and in greater detail, before these problems can be satisfactorily discussed and solved. It is obvious that in such a great series of eruptions as that of Central France, where over a comparatively limited area an alternation of basic and acid lavas has been many times repeated, the subterranean magma must have undergone a succession of changes in composition. Perhaps a definite cycle of such alternations may be made out. The sequence from basic to acid protrusions, observable among the British Palæozoic volcanic rocks, is suggestive of a separation of the more basic constituents of the magma with consequent increasing acidity of the residue. The earliest lavas mark the more basic condition of the magma, while the latest felsite and quartz-porphyry intrusions show its impoverishment in bases at the close of a volcanic period. During the interval before the next period the magma had in some way been renewed, for when eruptions began anew they were once more basic. But by the close of the volcanic activity the magma had again lost a large proportion of its basic constituents and had become decidedly acid.

Reference has already (p. 114) been made to the speculation of Durocher as to the existence within the crust of an upper siliceous layer with a mean of 71 per cent of silica, and a lower basic layer with about 51 per cent of silica. Bunsen also came to the conclusion that volcanic rocks are mixtures of two original normal magmas—the normal trachytic (with a mean of 76·67 silica), and the normal pyroxenic (with a mean of 47·48 silica). The varying proportions in which these two original magmas have been combined are, in Bunsen's view, the cause of the differences of volcanic rocks. We may conceive these two layers to be superposed upon each other, according to relative densities, and the composition of the last material erupted at the surface to depend upon the depth from which it has been derived.[167] The earliest explosions may be supposed to have taken place usually from the upper lighter and more siliceous layer, and the lavas ejected would consequently be in general acid, while later eruptions, reaching down to deeper and heavier zones of the magma, brought up such basic lavas as basalt. Certainly the general similarity of the volcanic rocks all over the globe would appear to prove that there must be considerable uniformity of composition in the zones of intensely hot material from which volcanic rocks are derived.[168]

Many difficulties, however, remain yet to be explained before our knowledge of volcanic action can be regarded as more than rudimentary. In Book IV. Part VII. a description is given of the part volcanic rocks have played in building up what we see of the earth's crust, and the student will there find other illustrations of facts and deductions which have been given in the previous pages.

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[167] See R. Bunsen, Pogg. Ann. lxiii. (1851), p. 204; Sartorius von Waltershausen, "Sicilien und Island," p. 416; Reyer, "Beitrag zur Physik der Eruptionen," iii. Scrope had long before suggested a classification of volcanic rocks into Trachyte, Graystone, and Basalt, Journ. Science, xxi.

[168] In the memoir by Captain Dutton, cited in a previous note, the hypothesis is maintained that the order of appearance of the lavas is determined by their relative density and fusibility, the most basic and heaviest, though most easily fused, requiring the highest temperature to diminish their density to such an extent as to permit them to be erupted.

Section ii. Earthquakes[169]

By the more delicate methods of observation which have been invented in recent years, it has been ascertained that the ground beneath our feet is apparently everywhere subject to continual slight tremors and to minute pulsations of longer duration. The old expression "terra firma" is not only not strictly true, but in the light of modern research seems singularly inappropriate. Rapid changes of temperature and atmospheric pressure, the fall of a shower of rain, the patter of birds' feet, and still more the tread of larger animals, produce tremors of the ground which, though exceedingly minute, are capable of being made clearly audible by means of the microphone and visible by means of the galvanometer. Some tremors of varying intensity and apparently of irregular occurrence, may be due to minute movements or displacements in the crust of the earth. Less

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[169] On the phenomena of earthquakes consult Mallet, Brit. Assoc. 1847, part ii. p. 30; 1850, p. 1; 1851, p. 272; 1852, p. 1; 1858, p. 1; 1861, p. 201; "The Great Neapolitan Earthquake of 1857," 2 vols., 1862; D. Milne, Edin. New Phil. Journ. xxxi.-xxxvi.; A. Perrey, Mem. Couronn. Bruxelles, xviii. (1844), Comptes rendus, lii. p. 146; Otto Volger, "Untersuchungen über die Phänomene der Erdbeben in der Schweiz," Gotha, 1857-58; Z. Deutsch. Geol. Ges. xiii. p. 667; R. Falb, "Grundzüge einer Theorie der Erdbeben und Vulkanensausbrüche," Graz, 1871; "Gedanken und Studien über den Vulkanismus, etc.," 1874; Pfaff, "Allgemeine Geologie als exacte Wissenschaft," Leipzig, 1873, p. 224. Records of observed earthquakes will be found in the memoirs of Mallet and Perrey; also in papers by Fuchs in Neues Jahrb. 1865-1871, and in Tschermak's Mineralog. Mittheilungen, 1873 and subsequent years. See also Schmidt, "Studien über Erdbeben," 2d edit. 1879; "Studien über Vulkane und Erdbeben," 1881; Dieffenbach, Neues Jahrb. 1872, p. 155; M. S. di Rossi, "La Meteorologia Endogena," 2 vols. 1879 and 1882; M. Gatta, "L'Italia, su vulcani e terremoti," 1882; J. Milne, "Earthquakes and other Earth-movements," 1886, and his beautifully illustrated volume on the Japan Earthquake of October, 1891. G. Mercalli, in his "Vulcani e Fenomeni Vulcanici in Italia" (1883), gives an account of the Italian earthquakes from 1450 B.C. to A.D. 1881; he separately describes the great Ischian earthquake of 1883; "L'Isola d'Ischia," Milan, 1884. Much interesting information will be found in the Bulletino del Vulcanismo Italiano, which began to be published in 1874; also in the Transactions of the Seismological Society of Japan—a society instituted in the year 1880 for the investigation of earthquake phenomena, especially in Japan, where they are of frequent occurrence. Other papers are quoted in the following pages.

easily traceable are the slow pulsations of the crust, which in many cases are periodic, and may depend on such causes as the diurnal oscillation of the thermal or barometric conditions of the atmosphere, the rise and fall of the tides, etc. So numerous and well marked are these tremors and pulsations, that the delicate observations which were set on foot to determine the lunar disturbance of gravity had to be abandoned, for it was found that the minute movements sought for were wholly eclipsed by these earth tremors.[170]

The term Earthquake denotes any natural subterranean concussion, varying from such slight tremors as to be hardly perceptible up to severe shocks, by which houses are levelled, rocks dislocated, landslips precipitated, and many human lives destroyed. The phenomena are analogous to the shock communicated to the ground by explosions of mines or powder-works. They may be most intelligibly considered as wave-like undulations propagated through the solid crust of the earth. In Mr. Mallet's language, an earthquake may be defined as "the transit of a wave of elastic compression, or of a succession of these, in parallel or intersecting lines through the solid substance and surface of the disturbed country." Mr. Milne has since remarked that the disturbance may also be due to the transit of waves of elastic distortion. The passage of the wave of shock constitutes the real earthquake.

Besides the wave of shock transmitted through the solid

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[170] A. d'Abbadie, "Etudes sur la verticale," 1872. Plantamour, Comptes rend. June, 1878, February, 1881; Archives Sciences Phys. Nat. Geneva, ii. p. 641; v. p. 97; vii. p. 601; viii. p. 551; x. p. 616; xii. (1884), p. 388. G. H. Darwin, Brit. Assoc. 1882, p. 95. In this paper Prof. Darwin discusses the amount of disturbance of the vertical near the coasts of continents, caused by the rise and fall of the tide. J. Milne, Trans. Seismological Soc. Japan, vi. (1883), p. 1; Geol. Mag. 1882, p. 482; Nature, xxvi. p. 125. The numerous observations made by Rossi in Italy are summarized by G. Mercalli in his work cited above, p. 332.

crust, waves are also propagated through the air, and, where the site of the impulse is not too remote, through the ocean. Earthquakes originating under the sea are numerous and specially destructive in their effects. They illustrate well the three kinds of waves associated with the progress of an earthquake. These are, 1st, The true earth-wave through the earth's crust; 2d, A wave propagated through the air, to which the characteristic sounds of rolling wagons, distant thunder, bellowing oxen, etc., are due; 3d, Two sea-waves, one of which travels on the back of the earth-wave and reaches the land with it, producing no sensible effect on shore; the other an enormous low swell, caused by the first sudden blow of the earth-wave, but travelling at a much slower rate, and reaching land often several hours after the earthquake has arrived.

Amplitude of earth-movements.—The popular conception of the extent to which the ground moves to and fro or up and down during an earthquake is a great exaggeration of the truth. As the result of very careful measurement with delicate instruments, there appears to be reason to believe that the horizontal motion at the time of a small earthquake is usually only the fraction of a millimetre, and seldom exceeds three or four millimetres. When the motion rises to five or six millimetres brick and stone chimneys are shattered. Yet even with such an intensity of shock a person walking in an open place might be quite unconscious of any perceptible movement of the ground. The vertical motion also appears to be exceedingly small.[171]

Velocity.—Experiments have been made to determine the

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[171] Milne "Earthquakes," pp. 75, 76. An ingenious model in wire has been made by Prof. Sekiya to illustrate the highly complex path pursued by a particle on the surface of the ground during an earthquake at Tokio, Japan, on 15th January, 1887.

velocity of the earth-wave, and its variation with the nature of the material through which it is propagated. Mr. Mallet found that the shock produced by the explosion of gunpowder travelled at the rate per second of 825 feet in sand; 1088 feet in schists, slates, and quartzites; 1306 feet in friable granite; and 1664 feet in solid granite. General Abbot, by observing the effects of the explosion of dynamite and gunpowder, found the velocity of transmission of the shock to vary from 1240 to 8800 feet per second, and to be greatest where the shock is most violent.[172] Observations of the time at which an earthquake has successively visited the different places on its track have shown similar variations in the rate of movement. Thus in the Calabrian earthquake of 1857, the wave of shock varied from 658 to 989 feet per second, the mean rate being 789 feet. The earthquake at Viège in 1855 was estimated to have travelled northward toward Strasburg at the rate of 2861 feet per second, and southward toward Turin at a rate of 1398 feet, or less than half the northern speed. The earthquake of 7th October, 1874, in northern Italy, travelled at rates varying from 273 to 874 feet per second. That of 12th March, 1873, showed a velocity per second of 2734 feet between Ragusa and Venice; 4101 feet from Spoleto to Venice; 601 feet from Perugia to Orvieto; 1640 feet from Perugia to Ancona; and 1640 (or 2188) feet from Perugia to Rome. The rate of the central European earthquake of 1872 was estimated to have been 2433 feet, that of Herzogenrath, June 24, 1877, 1555 feet, that of an earthquake at Travancore, in Southern Hin-

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[172] Amer. Journ. Sci. xv. (1878). Prof. J. Milne, experimenting in Japan, has likewise ascertained that a close relation exists between the initial violence of the shock and the velocity of propagation, and that there is a progressive diminution in speed as the wave of shock travels outward from the centre of disturbance. "Earthquakes," p. 65.

dustan, 656 feet in a second.[173] The most accurate measurements and computations of the velocity of earthquake movements are probably those made by Prof. J. Milne and his associates in Japan. The rates of movement during the Tokio earthquake of 25th October, 1881, are estimated to have ranged between 4000 and 9000 feet per second. As the result of prolonged observation, Prof. Milne concludes that "different earthquakes, although they may travel across the same country, have very variable velocities, varying between several hundreds and several thousands of feet per second; that the same earthquake travels more quickly across districts near to its origin than it does across districts which are far removed; and that the greater the intensity of the shock, the greater is the velocity." [174]

Duration.—The number of shocks in an earthquake varies indefinitely, as well as the length of the intervals between them. Sometimes the whole earthquake only lasts a few seconds; thus the city of Caracas, with its fine churches and 10,000 of its inhabitants, was destroyed in about half a minute; Lisbon was overthrown in five minutes. But a succession of shocks of varying intensity may continue for days, weeks, or months. The Calabrian earthquake, which began in February, 1783, was continued by repeated shocks for nearly four years until the end of 1786.

Modifying influence of geological structure.—In its pas-

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173 K. von Seebach, "Das Mitteldeutsche Erdbeben von 6 März, 1872," Leipzig, 1873. Höfer, Sitzb. Akad. Wien, Dec. 1876; A. von Lasaulx, "Das Erdbeben von Herzogenrath, 22d Oct., 1873," Bonn, 1874. "Das Erdbeben von Herzogenrath, 24 Juni, 1877," Bonn, 1878. G. C. Laube, on Earthquake of 31st January, 1883, at Trautenau, Jahrb. Geol. Reichs. 1883, p. 331. H. Credner, on the Earthquakes of the Erzgebirge and Vogtland from 1878 to 1884, Zeitsch. für Naturwiss. vol. lvii. (1884). F. Wähner, on Agram earthquake of 9 Nov. 1880, Sitz. Akad. Wien, lxxxviii. (1883), p. 15. Di Rossi, "Meteorologia Endogena," i. p. 306; P. Serpieri, Instituto Lombardo, 1873.

174 "Earthquakes," p. 94.

sage through the solid terrestrial crust from the focus of origin, the earth-wave must be liable to continual deflections and delays, from the varying geological structure of the rocks. To this cause, no doubt, must be in large measure ascribed the marked differences in the rate of propagation of the same earthquake in different directions. The wave of disturbance, as it passes from one kind of rock to another, and encounters materials of very different elasticity, or as it meets with joints, dislocations, and curva-

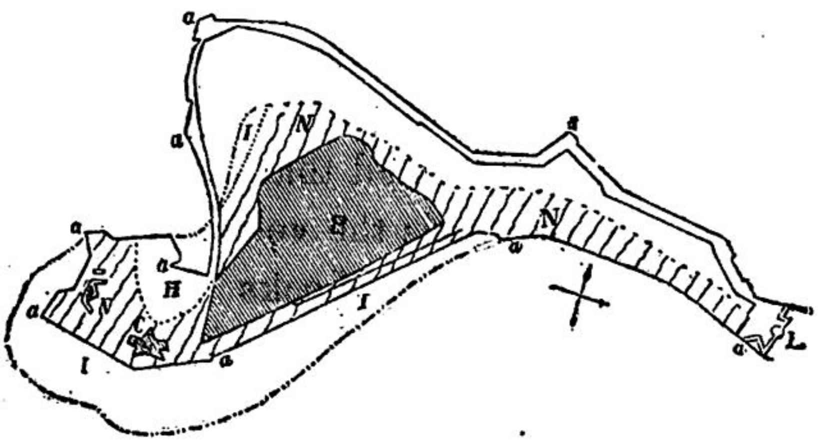

Fig. 71.—Plan of Port Royal, Jamaica, showing the effects of the Earthquake of 1692 (B.).

P C, Portions of the town built on limestone and left standing after the earthquake; *a a*, L, the boundary of the town prior to the earthquake; N N, Ground gained by the drifting of sand up to the end of last century; I L H, Additions from the same cause during the first quarter of the present century.

tures in the same rock, must be liable to manifold changes alike in rate and in direction of movement. Even at the surface, one effect of differences of material may be seen in the apparently capricious demolition of certain quarters of a city, while others are left comparatively scathless. In such cases, it has often been found that buildings erected on loose inelastic foundations, such as sand and clay, are more liable to destruction than those placed upon solid rock. In illustration of this statement the accompanying plan (Fig. 71) of Port Royal, Jamaica, was given by De la Beche[175] to show that the portions of the town which did not disappear during the earthquake of 1692 were built upon solid white limestone, while the parts built on sand were shaken to pieces.[176]

It has been observed that an earthquake shock will pass under a limited area without disturbing it, while the region all around has been affected, as if there were some superficial stratum protected from the earth-wave. Humboldt cited a case where miners were driven up from below ground by earthquake shocks not perceptible at the surface, and on the other hand, an instance where they experienced no sensation of an earthquake which shook the surface with considerable violence.[177] Such facts bring impressively before the mind the extent to which the course of the earth-wave must be modified by geological structure. In some instances, the shock extends outward from a common centre, so that a series of concentric circles may be drawn round the focus, each of which will denote a certain approximately uniform intensity of shock ("coseismic lines" of Mallet), this intensity, of course, diminishing with distance from the focus. The Calabrian earthquake of 1857 and that of Central Europe in 1872 may be taken in illustration of this central type. In other cases, however, the earthquake travels chiefly along a certain band or zone (particularly along the flanks of a mountain-chain) without advancing far from it laterally. This type of linear earthquake is exemplified by the frequent shocks which traverse

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175 "Geological Observer," p. 426.

176 The opposite effect has been observed on the island of Ischia, the houses built on loose subsoil generally having suffered much less than the others. There appears, indeed, to be a considerable conflict of testimony on this subject. See Milne, "Earthquakes," p. 130.

177 "Cosmos," Art. Earthquakes.

Chile, Peru, and Ecuador, between the line of the Andes and the Pacific coast.[178]

Extent of country affected.—The area shaken by an earthquake varies with the intensity of the shock, from a mere local tract where a slight tremor has been experienced, up to such catastrophes as that of Lisbon in 1755, which, besides convulsing the Portuguese coasts, extended into the north of Africa on the one hand and to Scandinavia on the other, and was even felt as far as the east of North America. Humboldt computed that the area shaken by this great earthquake was four times greater than that of the whole of Europe. The South American earthquakes are remarkable for the great distances to which their effects extend in a linear direction. Thus the strip of country in Peru and Ecuador severely shaken by the earthquake of 1868 had a length of 2000 miles.

Depth of source.—According to Mallet's observations, over the centre of origin the shock is felt as a vertical up-and-down movement (*Seismic vertical*); while, receding from this centre in any direction, it is felt as an undulatory movement, and comes up more and more obliquely. The *angle of emergence*, as he termed it, was obtained by him by taking the mean of observations of the rents and displacements of walls and buildings. In Fig. 72, for example, the wall there represented has been rent by an earthquake which emerged to the surface in the path marked by the arrow.

By observations of this nature, Mallet estimated the ap-

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[178] For a list of Peruvian earthquakes from A.D. 1570 to 1875, see Geograph. Mag. iv. (1877), p. 206. The earthquake of 9 May, 1877, at Iquique, and its ocean-wave are described by E. Geinitz, Nova Act. Ac. Cæs. Leopold. Car. xl. (1878), pp. 383–444.

proximate depth of origin of an earthquake. Let Fig. 73, for example, represent a portion of the earth's crust in which at *a* an earthquake arises. The wave of shock will travel outward in successive spherical shells. At the point

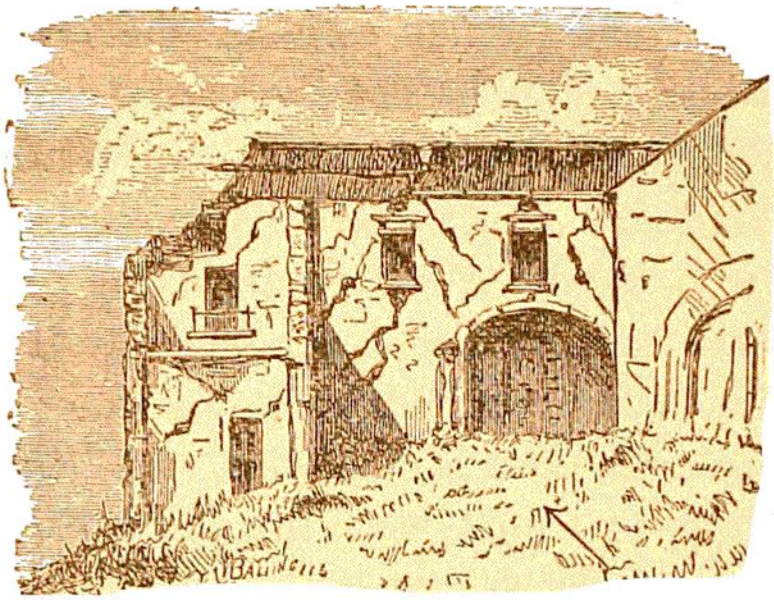

Fig. 72.—Wall shattered by an Earthquake, of which the "path of emergence" has been in the direction shown by the arrow. (After Mallet.)

e it will be felt as a vertical movement and loose objects, such as paving-stones, may be jerked up into the air, and descend bottom uppermost on their previous sites. At *d*, however, the wave will emerge at a lower angle, and will give rise to an undulation of the ground, and the oscillation of objects projecting above the surface. In rent buildings,

Fig. 73.—Mallet's mode of estimation of depth of source of Earthquake movements.

the fissures will be on the whole perpendicular to the path of emergence. By a series of observations made at different points, as at *g* and *f*, a number of angles are obtained, and the point where the various lines cut the vertical (*a*) will mark the area of origin of the shock. By this means, Mallet computed that the depth at which the impulse of the Calabrian earthquake of 1857 was given was about five miles. As the general result of his inquiries, he concluded that, on the whole, the origin of earthquakes must be sought in comparatively superficial parts of the crust, probably never exceeding a depth of 30 geographical miles. Following another method of calculation, Von Seebach computed that the earthquake which affected Central Europe in 1872 originated at a depth of 9·6 geographical miles; that of Belluno in the same year was estimated by Höfer to have had its source rather more than 4 miles deep; while that of Herzogenrath in 1873 was placed by Von Lasaulx at a depth of about 14¼ miles, and that of 1877 in the same region at about 14 miles.[179]

Geological Effects.—These are dependent not only on the strength of the concussion but on the structure of the ground, and on the site of the disturbance, whether underneath land or sea. They include changes superinduced on the surface of the land, on terrestrial and oceanic waters, and on the relative levels of land and sea.

1. Effects upon the soil and general surface of a country.—The earth-wave or wave of shock underneath a country may traverse a wide region and affect it violently at the time, without leaving permanent traces of its passage. Blocks of rock, however, already disengaged from their parent masses on declivities, may be rolled down into the valleys. Landslips are produced,

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[179] See papers by Höfer and A. von Lasaulx, cited on p. 463. For an account of the various methods employed in estimating the depth of origin of earthquakes, see Milne's "Earthquakes," chapters x. and xi. Consult also the Trans. Seismolog. Soc. Japan.

which may give rise to considerable subsequent changes of drainage. In some instances, the surfaces of solid rocks are shattered as if by gunpowder, as was particularly noticed to have taken place among the Primary rocks in the Concepcion earthquake of 1835.[180] It has often been observed also that the soil is rent by fissures which vary in size from mere cracks, like those due to desiccation, up to chasms a mile or more in length and 200 feet or more in depth. Permanent modifications of the landscape may thus be produced. Trees are thrown down, and buried, wholly or in part, in the rents. These superficial effects may, indeed, be soon effaced by the levelling power of the atmosphere. Where, however, the chasms are wide and deep enough to intercept rivulets, or to serve as channels for heavy rain-torrents, they are sometimes further excavated, so as to become gradually enlarged into ravines and valleys, as has happened in the case of rents caused by the earthquakes of 1811–12 in the Mississippi Valley. In the earthquake which shook the South Island of New Zealand in 1848, a fissure was formed, averaging 18 inches in width and traceable for a distance of 60 miles parallel to the axis of the adjacent mountain-chain. The subsequent earthquake of 1855, in the same region, gave rise to a fracture which could be traced along the base of a line of cliff for a distance of about 90 miles. Dr. Oldham has described a remarkable series of fissurings which ran parallel with the river of Calhar, Eastern British India, varying with it to every point of the compass and traceable for 100 miles.[181] The great Japanese earthquake of

[180] Darwin, "Journal of Researches," 1845, p. 303.

[181] Q. J. Geol. Soc. xxviii. p. 257. For a catalogue of Indian Earthquakes down to the end of 1869, see T. Oldham, Mem. Geol. Surv. India, xix. part 2.

28th October, 1891, gave rise to some remarkable fractures of the ground, in one of which one side was placed permanently at a different level from the other (Fig. 74).

Remarkable circular cavities have been noticed in Calabria and elsewhere, formed in the ground during the passage of the earth-wave. In many cases, these holes serve as funnels of escape for an abunbant discharge of water, so that

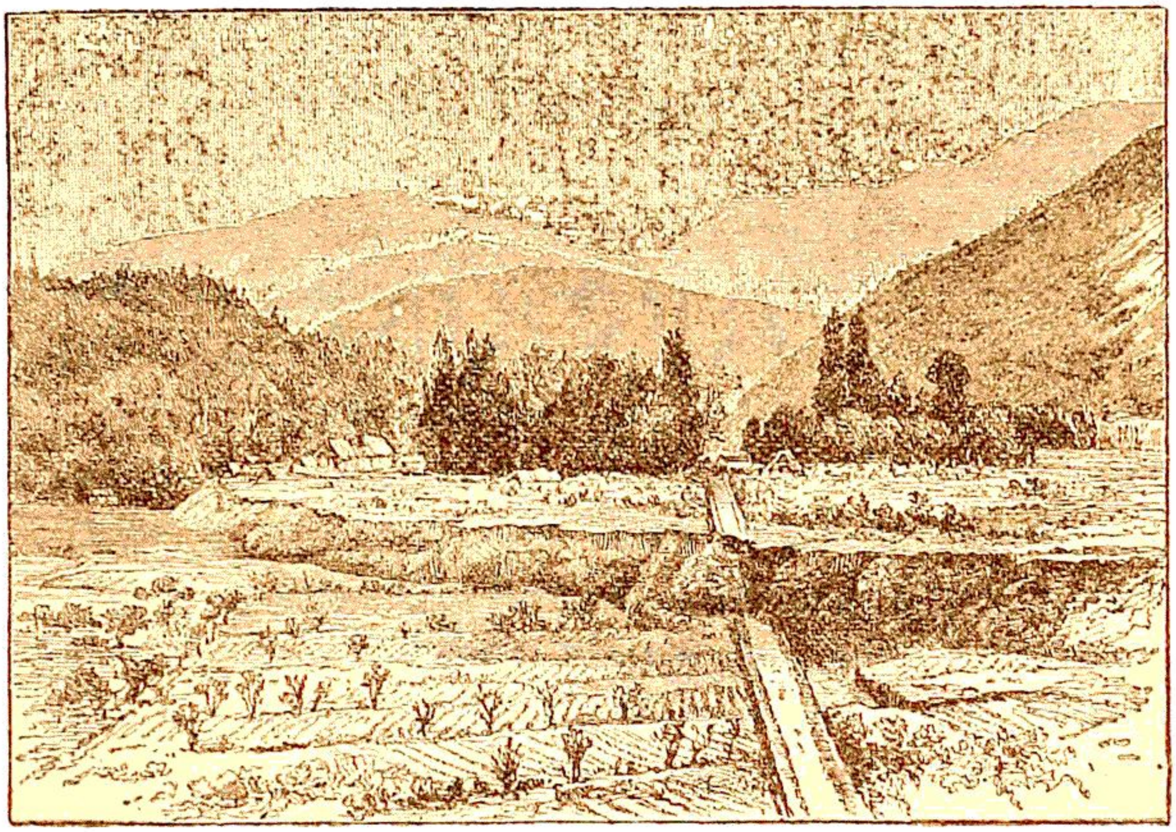

Fig. 74.—Fissure or fault caused by the earthquake of 28th October, 1891, in the Neo Valley, Japan.

when the disturbance ceases they appear as pools. They are believed to be caused by the sudden collapse of subterranean water-channels and the consequent forcible ejection of the water to the surface. Besides water, discharges of various gases and vapors, sometimes combustible, have been noted at the fissures formed during earthquakes.

2. Effects upon terrestrial waters.[182]—Springs

[182] Kluge, Neues Jahrb. 1861, p. 777.

are temporarily affected by earthquake movements, becoming greater or smaller in volume, sometimes muddy or discolored, and sometimes increasing in temperature. Brooks and rivers have been observed to flow with an interrupted course, increasing or diminishing in size, stopping in their flow so as to leave their channels dry, and then rolling forward with increased rapidity. Lakes are still more sensitive. Their waters occasionally rise and fall for several hours, even at a distance of many hundred miles from the centre of disturbance. Thus, on the day of the great Lisbon earthquake, many of the lakes of central and northwestern Europe were so affected as to maintain a succession of waves rising to a height of 2 or 3 feet above their usual level. Cases, however, have been observed where, owing to excessive subterranean movement, lakes have been emptied of their contents and their beds have been left permanently dry. On the other hand, areas of dry ground have been depressed, and have become the sites of new lakes.

Some of the most important changes in the fresh water of a region, however, are produced by the fall of masses of rock and earth, which, by damming up a stream, may so arrest its water as to form a lake. If the barrier be of sufficient strength, the lake will be permanent; though, from the usually loose, incoherent character of its materials, the dam thrown across the pathway of a stream runs a great risk of being undermined by the percolating water. A sudden giving way of the barrier allows the confined water to rush with great violence down the valley, and to produce perhaps tenfold more havoc there than may have been caused by the original earthquake. When a landslip is of sufficient dimensions to divert a stream from its previous course, the new channel thus taken may become permanent, and a valley may be cut out or widened.

3. Effects upon the sea.—The great sea-wave propagated outward from the centre of a sub-oceanic earthquake and reaching the land after the earth-wave has arrived there, gives rise to much destruction along the maritime parts of the disturbed region. When it approaches a low shore, the littoral waters retreat seaward, sucked up, as it were, by the advancing wall of water, which, reaching a height of sometimes 60 feet or more, rushes over the bare beach and sweeps inland, carrying with it everything which it can dislodge and bear away. Loose blocks of rock are thus lifted to a considerable distance from their former position, and left at a higher level. Deposits of sand, gravel, and other superficial accumulations are torn up and swept away, while the surface of the country, as far as the limit reached by the wave, is strewn with débris. If the district has been already shattered by the passage of the earth-wave, the advent of the great sea-wave augments and completes the devastation. The havoc caused by the Lisbon earthquake of 1755, and by that of Peru and Ecuador in 1868, was much aggravated by the co-operation of the oceanic wave. Where the wave breaks on land rising out of deep water little damage may be done.

4. Permanent changes of level.—It has been observed, after the passage of an earthquake, that the level of the disturbed country has sometimes been changed. Thus after the terrible earthquake of 19th November, 1822, the coast of Chile, for a long distance, was found to have risen from 3 to 4 feet, so that along shore, littoral shells were exposed still adhering to the rocks, amid multitudes of dead fish. The same coast-line has been further upraised

by subsequent earthquake shocks. On the other hand, many instances have been observed where the effect of an earthquake has been to depress permanently the disturbed ground. For example, by the Bengal earthquake of 1762, an area of 60 square miles on the coast near Chittagong suddenly went down beneath the sea, leaving only the tops of the higher eminences above water. The succession of earthquakes which in the years 1811 and 1812 devastated the basin of the Mississippi, gave rise to widespread depressions of the ground, over some of which, above alluded to, the river spread so as to form new lakes, with the tops of the trees still standing above the surface of the water.

Distribution of Earthquakes.[183]—While no large space of the earth's surface seems to be free from at least some degree of earthquake-movement, there are regions more especially liable to the visitation. As a rule, earthquakes are most frequent in volcanic districts, the explosions of a volcano being generally preceded or accompanied by tremors of greater or less intensity. In the Old World, a great belt of earthquake disturbance stretches in an east and west direction, along that tract of remarkable depressions and eleva-

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[183] For European earthquakes an alphabetical catalogue has been compiled by Prof. O'Reilly, Trans. Roy. Irish Academy, xxviii. (1886), p. 489. Catalogue of British earthquakes, op. cit. xxviii. (1884), p. 285. C. Davidson, Geol. Mag. 1891, p. 450. Quart. Journ. Geol. Soc. xlvii. (1891), p. 618. Detailed observations of the effects of some recent European earthquakes will be found in the following Memoirs. The Andalusian earthquake of 25th Dec. 1884, T. Taramelli and G. Mercalli, Real. Accad. Lincei, 1885–86, p. 116, Hébert, Compt. Rend. 1885, Fouqué, ibid. 20th April, 1885, and the large quarto volume of reports by the mission specially sent to study the phenomena of this earthquake, Memoires Acad. Sci. 1889; the Ligurian earthquake of 23d Feb. 1887, T. Taramelli and G. Mercalli, Ann. Ufficio Centrale Meteorolog. Geodinam. part iv. vol. viii. (1888), Real. Accad. Lincei, iv. (1888); the Agram earthquake of 9th Nov. 1880, "Grundzüge der Abyssodynamik," etc., by S. Pilar, Agram, 1881; the middle German earthquake of 6th March, 1872, "Das Mitteldeutsche Erdbeben von 6 März, 1872," by K. von Seebach, Leipzig, 1873. See also the papers cited on pp. 459–465.

tions lying between the Alps and the mountains of northern Africa, and spreading eastward so as to inclose the basins of the Mediterranean, Black Sea, Caspian, and Sea of Aral, and to rise into the great mountain-ridges of Central Asia. In this zone lie numerous volcanic vents, both active and extinct or dormant, from the Azores on the west to the basaltic plateaus of India on the east. The Pacific Ocean, surrounded with a vast ring of volcanic vents, has its borders likewise subject to frequent earthquake shocks. Some of the most terrible earthquakes within human experience have been those which have affected the western seaboard of South America.[184] It is worthy of notice that the coasts of the Pacific Ocean more specially liable to convulsions of this nature plunge steeply down into deep water with slopes of one in twenty to one in thirty, while shore-lines such as those of Australia, Scandinavia, and the east of South America, where the slope is no more than from one in fifty to one in two hundred and fifty, are hardly ever affected by earthquakes. It should also be remarked that while earthquakes are apt to occur along the flanks of mountain-chains and to travel along these lines of elevation, they seldom cross a large mountain-chain. In some regions the site of disturbance is not on land but under the sea. This has been clearly established for Japan.[185]

Origin of Earthquakes.—Though the phenomena of an earthquake become intelligible as the results of the transmission of waves of shock arising from a centre where some

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[184] The Charleston Earthquake of 31st August, 1886, has been fully discussed by Captain Dutton, Ninth Ann. Report U. S. Geol. Survey, 1887–88, p. 209. The earthquakes of Central America are discussed by F. de Montessus de Ballore in a Memoir rewarded by the Acad. Sci. Nat. Saone et Loire, and published at Dijon, 1888.

[185] Milne, "Earthquakes," p. 227.

sudden and violent impulse has been given within the terrestrial crust, the origin of this sudden blow can only be conjectured. Various conceivable causes may, at different times and under different conditions, communicate a shock to the subterranean regions. Such are the sudden flashing into steam of water in the spheroidal state, the sudden condensation of steam, the explosions of a volcanic orifice, the falling in of the roof of a subterranean cavity, or the sudden snap of deep-seated rocks subjected to prolonged and intense strain.

In volcanic regions, the frequent earthquakes which precede or accompany eruptions are doubtless traceable to explosions of elastic vapors, and notably of steam. As earthquakes originate also in districts remote from any active volcano, and, so far as observation shows, at comparatively shallow depths, these cannot be connected with ordinary volcanic action, though it is possible that by movements of molten or highly-heated matter within the crust and its invasion of the upper layer, to which meteoric water in considerable quantities descends, sudden and extensive generation of steam may occasionally take place.[186] In minor cases, where the tremor is comparatively slight and local, we may conceive that the collapse of the roof or sides of some of the numerous tunnels and caverns dissolved out of underground rocks by permeating water may suffice to produce the observed shocks.[187] The copious discharge of materials from a volcanic vent may produce a cavity within the

[186] Pfaff, "Allgemeine Geologie als exacte Wissenschaft," p. 230.

[187] In the Visp Thal, Canton Wallis, for example, where there are some twenty springs carrying up gypsum in solution (one of them to the extent of 200 cubic metres annually), continued rumblings and sharp shocks are from time to time experienced. In July and August, 1855, these movements lasted upward of a month, and gave rise to the fissuring of buildings and the precipitation of landslips. In the honeycombed limestone tract of the Karst, also, earthquakes of varied intensity are of constant occurrence.

earth, the crushing in of which will give rise to earthquakes. There appears reason to believe that the most convulsive earthquakes originate under the sea, as in the cases of the great Lisbon earthquake and those of Peru, Chile, and Japan. For these it is as yet difficult to imagine an adequate cause. Prof. Milne believes that they may be partly due to disturbances of the nature of volcanic explosions, because they originate beneath the sea, and the vibrations have the peculiar rapid inward motion characteristic of the discharge of an explosive like dynamite.[188]

An obvious source of disturbance within the earth is the rupture of rocks within the crust under the intense strain produced by subsidence upon the more rapidly contracting inner hot nucleus. This cause may conceivably affect mountainous areas; but we do not know how it would affect the sea-floor. In mountainous districts, many different degrees of shock, from mere tremors up to important earthquakes, have been observed, and these are not improbably due to sudden more or less extensive fractures of rocks still under great strain.[189] Hoernes, from a study of European earthquake phenomena, concludes that though some minor earth-tremors may be due to the collapse of underground caverns, and others of local character to volcanic action, the greatest and most important earthquakes are the immediate consequences of the formation of mountains, and he connects the lines followed by earthquakes with the structural lines of mountain-axes.[190]

From what was stated at the beginning of the present section, it is evident that where the earth's crust in any region

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[188] "Earthquakes," p. 281.
[189] See postea, p. 530. Suess, "Entstehung der Alpen," Vienna, 1875.
[190] "Erdbeben Studien," Jahrb. Geol. Reichs. xxviii. (1878), p. 448.

is in a critical condition of equilibrium, some connection may be expected to be traceable between the frequency of earthquakes and the earth's position with regard to the moon and sun, on the one hand, and changes of atmospheric conditions, on the other. A comparison of the dates of recorded earthquakes seems to bear out the following conclusions: 1st. An earthquake maximum occurs about the time of new moon; 2d. Another maximum appears two days after the first quarter; 3d. A diminution of activity occurs about the time of full moon; 4th. The lowest earthquake minimum is on the day of the last quarter.[191] There is likewise observable a seasonal maximum and minimum, earthquakes over most of the northern hemisphere occurring most frequently in winter, and least frequently in summer.[192] Out of 656 earthquakes chronicled in France up to the year 1845, three-fifths took place in the winter, and two-fifths in the summer months. In Switzerland they have been observed to be about three times more numerous in winter than in summer. The same fact is remarked in the history even of the slight earthquakes in Britain. A daily maximum appears to occur about 2.30 A.M., and a minimum about three-quarters of an hour after noon. No connection has yet been satisfactorily established between the occurrence of earthquakes and sun-spots. The greater frequency of earthquakes in winter might be expected to indicate a relation between their occurrence and atmospheric pressure, and possibly earthquakes are more frequent with a low than with a high barometer.[193]

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[191] J. F. J. Schmidt, "Studien über Erdbeben," 2d ed. (1879), p. 18.

[192] Ibid. p. 20. See the works of Perrey cited on p. 459.

[193] Schmidt, op. cit. p. 23. F. Gröger, Neues Jahrb. 1878, p. 928. There does not appear to be any marked connection between the state of the barometer and the occurrence of earthquakes in Japan—J. Milne, "Earthquakes," p. 268.

Section iii. Secular Upheaval and Depression

Besides scarcely perceptible tremors and more or less violent movements due to earthquake-shocks, the crust of the earth is generally believed to undergo in many places oscillations of an extremely quiet and uniform character, sometimes in an upward, sometimes in a downward direction. So tranquil may these changes be, as to produce from day to day no appreciable alteration in the aspect of the ground affected, so that only after the lapse of several generations, and by means of careful measurements, can they really be proved. Indeed, in the interior of a country nothing but a series of accurate levellings from some unmoved datum-line might detect the change of level, unless the effects of the terrestrial disturbance showed themselves in altering the drainage. Only along the sea-coast is a ready measure afforded of any such movement.

It is customary in popular language to speak of the sea rising or falling relatively to the land. We cannot conceive of any possible augmentation of the oceanic waters, nor of any diminution, save what may be due to the extremely slow processes of abstraction by the hydration of minerals and absorption into the earth's interior. Any changes, therefore, in the relative levels of sea and land must be due to some readjustment in the form either of the solid globe or of its watery envelope or of both. Playfair argued at the beginning of this century that no subsidence of the sea-level could be local, but must extend over the globe.[194] But it is now recognized that what is called the sea-level cannot pos-

[194] "Illustrations of the Huttonian Theory," 1802. The same conclusion was announced by L. von Buch, "Reise durch Norwegen und Lapland," 1810.

sess the uniformity formerly attributed to it; that on the contrary it must be liable to local distortion from the attractive influence of the land. Not only so, but the level of the surface of large inland sheets of water must be affected by the surrounding high lands.

Mr. R. S. Woodward, whose recent memoir on this subject has been cited (p. 68), has calculated that in a lake 140 miles broad and 1000 feet deep in the middle, the difference of level of the water-surface at the centre and at the margin may amount to between three and four feet.[195] As already stated he has further computed that the effect of the continents of Europe and Asia at the centre in disturbing the sea-level must amount to about 2900 feet, if we suppose that there is no deficiency of density underneath the continent, and to only about 10 feet if we suppose that the very existence of the continent implies such a deficiency.[196]

Various suggestions have been made regarding possible causes of alteration of the sea-level. (1) A shifting of the present distribution of density within the nucleus of the planet would affect the position and level of the oceans (*ante*, p. 89). (2) As permanent snow and ice represent so much removed from the general body of water on the globe, any large increase or diminution in the extent and thickness of the polar ice-caps must cause a corresponding variation in the sea-level (*ante*, p. 44). (3) A change in the earth's centre of gravity, such as might result from the accumulation of large masses of snow and ice as an ice-cap at one of the poles, has been already referred to (p. 43) as tending to raise the level of the ocean in the hemisphere so affected, and to

[195] Bull. U. S. Geol. Surv. No. 48 (1888), p. 59.

[196] Op. cit. p. 85. See Stokes, Trans. Camb. Phil. Soc. viii. (1849), p. 672; Sci. Proc. Roy. Dublin Soc. v. (1887), p. 652.

diminish it in a corresponding measure elsewhere. The return of the ice into the state of water would produce an opposite effect. The attractive influence of the ice-sheets of the Glacial Period upon the sea-level over the northern hemisphere has been discussed by various mathematicians, especially by Croll, Pratt, Heath, and Lord Kelvin. Considerable differences appear in their results, according to the conditions which they postulate, but they agree that a decided elevation of the sea-level must be attributed to the accumulation of thick masses of snow and ice. The rise of the sea-level along the border of an ice-cap of 38° angular radius and 10,000 feet thick in the centre is estimated at from 139 to 573 feet.[197] (4) A still further conceivable source of geographical disturbance is to be found in the fact that, as a consequence of the diminution of centrifugal force owing to the retardation of the earth's rotation caused by the tidal wave, the sea-level must have a tendency to subside at the equator and rise at the poles.[198] A larger amount of land, however, need not ultimately be laid bare at the equator, for the change of level resulting from this cause would be so slow that, as Dr. Croll has pointed out,

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[197] See Croll, "Climate and Time," chaps. xxiii., xxiv. Geol. Mag, 1874. Pratt, "Figure of the Earth," D. D. Heath, Phil. Mag. xxxi. (1866), pp. 201, 323, xxxii. (1866), p. 34. Thomson (Lord Kelvin), op. cit. xxxi. p. 305. A. Penck, Jahrb. Geograph. Gesel. Munich, vii. De Lapparent, Bull. Soc. Geol. France, xiv. 1886, p. 368, Revue Generale des Sciences, May, 1890. R. S. Woodward, Bull. U. S. Geol. Survey, No. 48. Von Drygalski, "Bewegungen der Kontinente zur Eiszeit," Berlin, 1889. Prof. Suess believes that the limits of the dry land depend upon certain large indeterminate oscillations of the statical figure of the oceanic envelope; that not only are "raised beaches" to be thus explained, but that there are absolutely no vertical movements of the crust save such as may form part of the plication arising from secular contraction; and that the doctrine of secular fluctuations in the level of the continents is merely a remnant of the old "Erhebungstheorie," destined to speedy extinction. "Antlitz der Erde," Leipzig, 1883. Pfaff defends the general opinion against these views in Zeitsch. Deutsch. Geol. Ges. 1884.

[198] Croll, Phil. Mag. 1868, p. 382. Thomson, Trans. Geol. Soc. Glasgow, iii. p. 223

the general degradation of the surface of the land might keep pace with it and diminish the terrestrial area as much as the retreat of the ocean tended to increase it. The same writer has further suggested that the waste of the equatorial land, and the deposition of the detritus in higher latitudes, may still further counteract the effects of retardation and the consequent change of ocean-level. (5) Some geologists have supposed that where the earth's crust is loaded with thick deposits of sediment or massive ice-sheets it will tend to sink, while on the other hand denudation by unloading it promotes upheaval.

The balance of evidence at present available seems adverse to any theory which would account for ancient and modern changes in the relative level of sea and land by variations in the figure of the oceanic envelope, save to a limited extent by the attraction caused by extensive masses of upraised land, and possibly in northern and southern latitudes by the attractive influence of large accumulations of snow and ice. Such changes are rather to be regarded as due to movements of the solid crust. The proofs of upheaval and subsidence, though sometimes obtainable from wide areas, are marked by a want of uniformity and a local and variable character, indicative of an action local and variable in its operations, such as the folding of the terrestrial crust, and not regular and widespread, such as might be predicated of any alteration of sea-level. While admitting therefore that, to a certain extent, oscillations of the relative level of sea and land may have arisen from some of the causes above enumerated, we may hold that, on the whole, it is the land which rises and sinks rather than the sea.[199]

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[199] For the arguments against the view above adopted and in favor of the doctrine that the increase of the land above sea-level is due to the retirement of

§ 1. **Upheaval.**—Various maritime tracts of land have been ascertained to have undergone in recent times, or to be still undergoing, what appears to be a gradual elevation above the sea. On the coast of Siberia, for 600 miles to the east of the river Lena, round the islands of Spitzbergen and Novaja Zemlja, along the shores of the Scandinavian peninsula with the exception of a small area at its southern apex, and along a maritime strip of western South America, it has been proved that the sea stands now at a lower level with regard to the land than it formerly did. In searching for proofs of such movements the student must be on his guard against being deceived by any apparent retreat of the sea, which may be due merely to the deposit of gravel, sand, or mud along the shore, and the consequent gain of land. Local accumulations of gravel, or "storm beaches," are often thrown up by storms, even above the level of ordinary high-tide mark. In estuaries, also, considerable tracts of low ground are gradually raised above the tide-level by the slow deposit of mud. The following proofs of actual rise of the land are chiefly relied on by geologists.[200]

Evidence from dead organisms.—Rocks covered with barnacles or other littoral adherent animals, or pierced by lithodomous shells, afford presumptive proof of the presence of the sea. A single stone with these creatures on its surface would not be satisfactory evidence, for it might have been cast up by a storm; but a line of large bowlders, which had evidently not been moved since the cirripeds and mollusks lived upon them, and still more a solid cliff with these marks of littoral or sub-littoral life

the sea, see H. Trautschold, Bulletin Societe Imp. des Naturalistes de Moscou, xlii. (1869), part i. p. 1; 1883, No. 2, p. 341; Bull. Soc. Geol. France (3), viii. (1879), p. 134; but more especially Suess, in his great work the "Antlitz der Erde."

[200] See "Earthquakes and Volcanoes" (A. G.), Chambers's Miscellany of Tracts.

upon its base, now raised above high-water mark, would be sufficient to demonstrate a change of level. The amount of this change might be pretty accurately determined by measuring the vertical distance between the upper edge of the barnacle zone upon the upraised rock, and the limit of the same zone on the present shore. By this kind of evidence, the recent uprise of the coast of Scandinavia has been proved. The shell-borings on the pillars of the temple of Jupiter Serapis in the Bay of Naples prove first a depression and then an elevation of the ground to the extent of more than twenty feet.[201] Raised coral-reefs, formed by living species of corals, are a conspicuous feature of the geology of the West Indian Region. The terraces of Barbadoes are particularly striking. In Cuba, a raised coral-reef occurs at a height of 1000 or 1100 feet above the sea.[202] In Peru, modern coral-limestone has been found 2900 or 3000 feet above sea-level.[203] Again, in the Solomon Islands, evidence of recent uprise is furnished by coral-reefs lying at a height of 1100 feet,[204] and similar evidence occurs among the New Hebrides at 1500 feet.

The elevation of the sea-bottom can in like manner be proved by dead organisms fixed in their position of growth beneath high-water mark. Thus dead specimens of *Mya truncata* occur on some parts of the coast of the Firth of Forth in considerable numbers, still placed with their siphuncular end uppermost in the stiff clay in which they burrowed. The position of these shells is about high-water mark, but as their existing descendants do not live above low-water mark, we may infer that the coast has been raised by at least the difference between high- and low-water mark, or eighteen feet.[205] Dead shells of the large *Pholas dactylus* occur in a similar position near high-water mark on the Ayrshire coast. Even below low-water, examples have been noted, as in the interesting case observed by Sars on the Dröbaksbank in the Christiania Fjord, where dead stems of *Oculina prolifera* (L.) occur at depths of only ten or fifteen fathoms. This coral is really a deep-sea form, living on the western and northern coasts of Norway, at

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[201] Babbage, Edin. Phil. Journ. xi. (1824), p. 91. J. D. Forbes, Edin. Journ. Sci. i. (1829), p. 260. Lyell, "Principles," ii. p. 164.

[202] A. Agassiz, Amer. Acad. xi. (1882), p. 119.

[203] A. Agassiz, Bull. Mus. Comp. Zool. vol. iii.

[204] H. B. Guppy, Nature, 3d January, 1884.

[205] Hugh Miller's "Edinburgh and its Neighborhood," p. 110.

depths of one hundred and fifty to three hundred fathoms in cold water. It must have been killed as the elevation of the area brought it up into upper and warmer layers of water.[206] It has even been said that the pines on the edges of the Norwegian snow-fields are dying in consequence of the secular elevation of the land bringing them up into colder zones of the atmosphere.

Any stratum of rock containing marine organisms which have manifestly lived and died where their remains now lie, may be held to prove a change of level between sea and land. In this way it can be shown that most of the solid

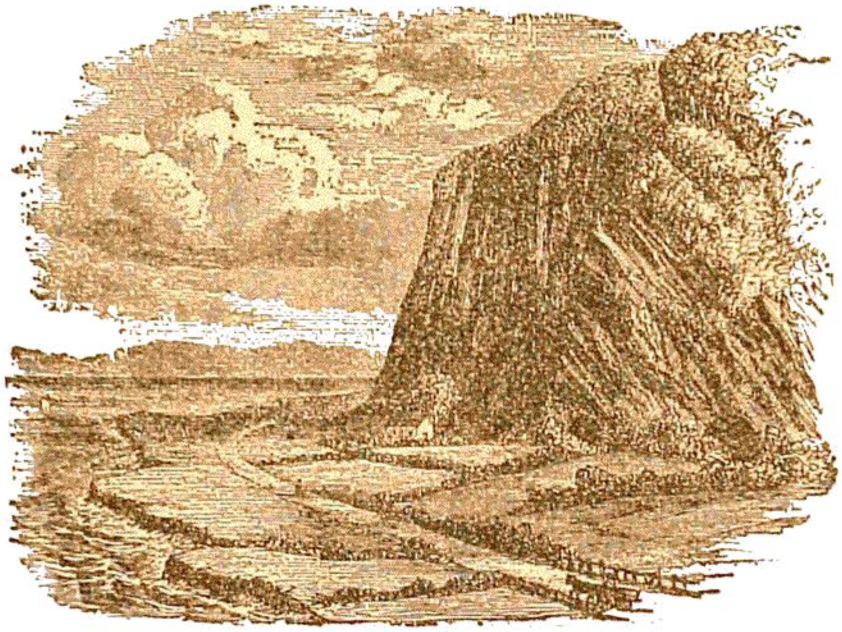

Fig. 75.—View of a line of ancient sea-cliff pierced at the base with sea-worn caves and fronted by a Raised Beach.

land now visible to us has once been under the sea. High on the flanks of mountain-chains (as in the Alps and Himalayas), undoubted marine shells occur in the solid rocks.

Sea-worn Caves.—A line of sea-worn caves, now standing at a distance above high-water mark beyond the reach of the sea, affords evidence of recent change of level. In the accompanying diagram (Fig. 75) examples of such caves are seen at the base of the cliff, once the sea-margin, now separated from the tide by a platform of meadow-land.

Raised Beaches furnish one of the most striking

[206] Quoted by Vom Rath in a paper entitled "Aus Norwegen," Neues Jahrb. 1869, p. 422. For another example, see Gwyn Jeffreys, Brit. Assoc. 1867, p. 431.

proofs of change of level. A beach or space between tide-marks, where the sea is constantly grinding down sand and gravel, mingling with them the remains of shells and other organisms, sometimes piling the deposits up, sometimes sweeping them away out into opener water, forms a familiar terrace or platform on coast-lines skirting tidal seas. When this margin of littoral deposits has been placed above the reach of the waves, the flat terrace thus elevated is known as a "raised beach" (Figs. 75, 76, 77, 78). The former high-water mark then lies inland, and while its sea-worn caves are in time hung with ferns and mosses, the beach across which the tides once flowed furnishes a platform on which meadows, fields, gardens, roads, houses, villages, and towns spring up, while a new beach is made below the margin of the uplifted one. A series of raised beaches may occur at various heights above the sea. Each terrace marks a former lower level of the land with regard to the sea, and probably a lengthened stay of the land at that level, while the intervals between them represent the vertical amount of each variation in the relative levels of sea and land, and show that the interval between the changes was too brief for the formation of terraces. A succession of raised beaches, rising above the present sea-level, may therefore be taken as pointing to a former intermittent upheaval of the country, interrupted by long pauses, during which the general level did not materially change, unless in regions where there is reason to believe that the surface of the sea has undergone a change of level from the accumulation or melting of large masses of snow and ice (*ante*, p. 43).

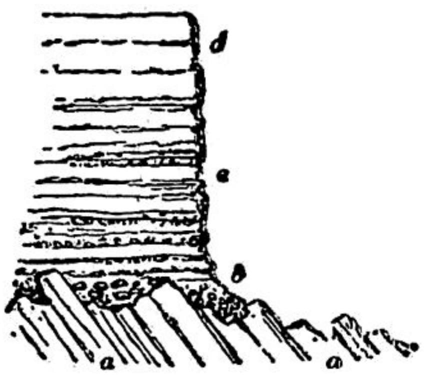

Fig. 76.—Section of a Raised Beach composed of gravel and sand (*b c*) resting on upturned slates (*a*), and passing up into blown sand (*d*) compacted by the decay of abundant land-shells. Fistrall Bay, Cornwall (*B.*).

Raised beaches abound in the higher latitudes of the northern and southern hemispheres, and this distribution has been claimed as a strong argument in favor of the view that they are due to a fall of the local level of the sea-surface from the disappearance or diminution of former ice-caps. That some at least of the raised beaches in these regions may be due to this cause may be granted. The gradual rise of level of the beaches when traced up the fjords, which has been repeatedly asserted for some districts, would be the natural effect of the greater mass of ice in the interior. In the exploration of the lake regions of North America numerous instances have been described of a slope upward of the former water-levels toward the main ice-fields. A remarkable example is furnished by the terraces of the vanished glacial sheet of water called Lake Agassiz which once filled the basin of the Red River of the North. Mr. Warren Upham has found that these ancient lines of water-level gradually rise from south to north and from west to east, in the direction of the former ice-fields, the amount of slope ranging from zero to 1·3 feet per mile.[207] Mr. G. K. Gilbert has noticed a rise of as much as 5 feet in a mile among the old terraces of Lake Ontario.[208]

Raised beaches occur round many parts of the coast-line of Britain. De la Beche gives the subjoined view (Fig. 77)

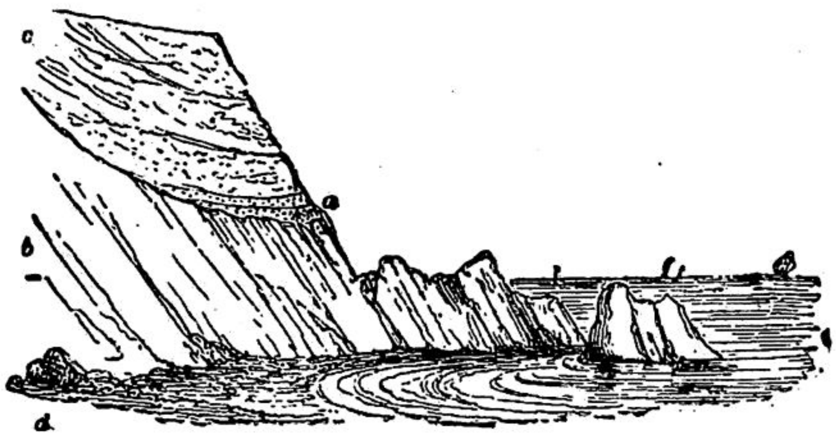

Fig. 77.—View of Raised Beach, Nelly's Cave, Cornwall (*B.*).

of a Cornish locality where the existing beach is flanked by a cliff of slate, *b*, continually cut away by the sea so that the overlying raised beach, *a*, *c*, will ere long disappear. The coast line on both sides of Scotland is likewise fringed with raised beaches, sometimes four or five occurring above each other at heights of 25, 40, 50, 60, 75, and 100 feet above the present high-water mark.[209] Others are found on both sides of the English Channel.[210] The sides of the

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[207] Bull. U. S. Geol. Surv. No. 39 (1887), pp. 18, 20.

[208] Science, i. p. 222.

[209] For accounts of some British raised beaches, see De la Beche, "Report on Geology of Devon and Cornwall," chap. xiii.; C. Maclaren, "Geology of Fife and the Lothians," 1839; R. Chambers, "Ancient Sea Margins"; Prestwich, Q. J. Geol. Soc. xxviii. p. 38; xxx. p. 29; R. Russell and T. V. Holmes, Brit. Assoc. 1876, Sects. p. 95; Ussher, Geol. Mag. 1879, p. 166.

[210] On the raised beach of Sangatte, near Calais, see Prestwich, Bull. Soc.

mountainous fjords of Northern Norway, up to more than 600 feet above sea-level, are marked with conspicuous lines of terraces (Fig. 78). These terraces are partly ordinary beach deposits, partly notches cut out of rock, probably with the aid of drifting coast-ice.[211] Proofs of recent elevation of the shores of the Mediterranean are furnished by raised beaches at various heights above the present water-level. In Corsica such terraces occur at heights of from 15 to 20 metres.[212]

On the west coast of South America, lines of raised terrace containing recent shells have been traced by Darwin

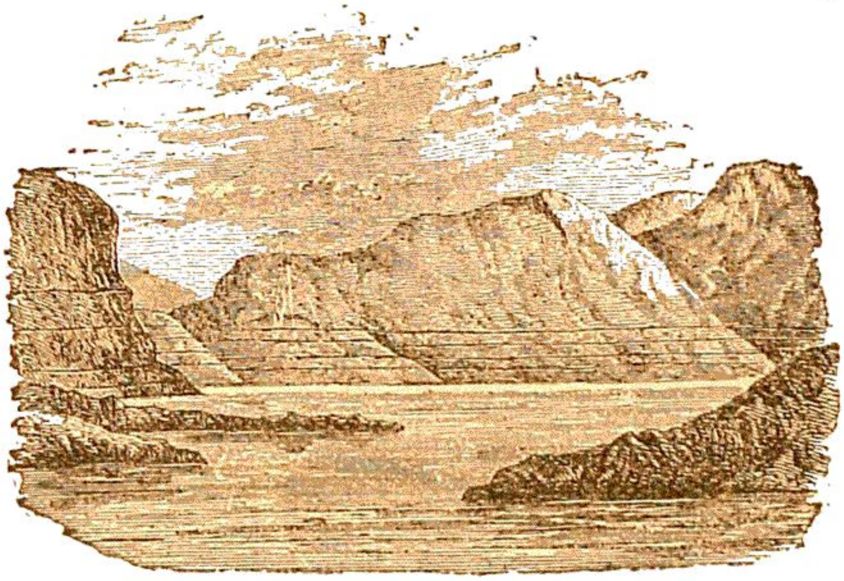

Fig. 78.—View of Terraces, Alten Fjord, Norway.

as proofs of a great upheaval of that part of the globe in modern geological time. The terraces are not quite horizontal but rise toward the south. On the frontier of Bolivia, they occur at from 65 to 80 feet above the existing sea-level,

Geol. France (3), viii. (1880), p. 547; on those of Finisterre, C. Barrois, Ann. Soc. Geol. Nord. ix. (1882).

[211] See R. Chambers, "Tracings of the North of Europe" (1850), p. 172 *et seq.* Bravais, "Voyages de la Commission Scientifique du Nord," etc., translated in Q. J. Geol. Soc. i. p. 534. Kjerulf, Z. Deutsch. Geol. Ges. xxii. p. 1; "Die Geologie des süd. und mittl. Norwegen," 1880, p. 7; Geol. Mag. viii. p. 74. S. A. Sexe, "On Rise of Land in Scandinavia," Index Scholarum of University, Christiania, 1872. H. Möhn. Nyt. Mag. Nat. xxii. p. 1. Dakyns, Geol. Mag. 1877, p. 72. K. Pettersen, Arch. Math. Nat. Christiania, 1878, p. 182, x. (1885); Geol. Mag. 1879, p. 298; Tromsö Museums Aarshefter, III. 1880. Sitz. Akad. Wien. xcviii. (1889). Lehmann, "Ueber-ehemalige Strandlinier," etc., Halle, 1879; Zeitsch. ges. Naturwiss. 1880, p. 280. A. G. Högbom, Geol. För. Förhandl. Stockholm, ix. 1887, p. 19. C. Sandler, Petermann's Mittheil. xxxvi. (1890), pp. 209, 235.

[212] Bull. Soc. Geol. France (3), iv. p. 86.

but nearer the higher mass of the Chilean Andes they are found at 1000, and near Valparaiso at 1300 feet. That some of these ancient sea-margins belong to the human period was shown by Mr. Darwin's discovery of shells with bones of birds, ears of maize, plaited reeds and cotton thread, in one of the terraces opposite Callao at a height of 85 feet.[213] Raised beaches occur in New Zealand, and indicate a greater change of level in the southern than in the northern part of the country.[214] It should be observed that this increased rise of the terraces poleward occurs both in the northern and southern hemispheres, and is one of the chief facts insisted upon by those who would explain the terraces by displacements of the sea rather than of the land.

Human Records and Traditions.—In countries which have been long settled by a human population, it is sometimes possible to prove, or at least to render probable, the fact of recent change of level by reference to tradition, to local names, and to works of human construction. Piers and harbors, if now found to stand above the upper limit of high-water, furnish indeed indisputable evidence of a rise of land or fall of sea-level since their erection. Numerous proofs of a recent change of level in the coast of the Arctic Ocean from Spitzbergen eastward have been observed. The Finnish coast is reported to have risen 6 feet 4 inches in 127 years.[215] At Spitzbergen itself, besides its raised beaches, bearing witness to previous elevations, small islands which existed two hundred years ago are now joined to larger portions of land. At Novaja Zemlja, where six raised beaches were found by Nordenskiöld, the highest being 600 feet above sea-level,[216] there seems to have been a rising of the sea-bottom to the extent of 100 feet or more since the Dutch expedition of 1594. On the north coast of Siberia the island of Diomida, observed in 1760 by Chalaourof to the east of Cape Sviatoj, was found by Wrangel sixty years afterward to have been united to the mainland.[217] From marks made on the coast in the middle

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213 "Geological Observations," chap. x. See Geol. Mag. 1877, p. 28.

214 Haast's "Geology of Canterbury," 1879, p. 366.

215 Nature, xxvi. p. 231.

216 Ibid. xv. p. 123.

217 Grad, Bull. Soc. Geol. France, 3d ser. ii. p. 348. Traces of oscillations of level within historic times have been observed in the Netherlands, Flanders and Upper Italy. Bull. Soc. Geol. France, 2d ser. xix. p. 556; 3d ser. ii. pp. 46, 222; Ann. Soc. Geol. Nord. v. p. 218. For alleged changes of level in the estuary of the Garonne, see Artigues, Act. Soc. Linn. Bordeaux, xxxi. (1876), p. 287, and Delfortrie, ib. xxxii. p. 79.

of last century it appears that the north of Sweden has risen about 7 feet in the last 154 years, but that the movement has lessened southward until in Scania it has been replaced by one in a downward direction (see p. 493).

§ 2. **Subsidence.**—It is more difficult to trace a downward movement of land, for the evidence of each successive sea-margin is carried down and washed away or covered up. The student will take care to guard himself against being misled by mere proofs of the advance of the sea on the land. In the great majority of cases, where such an advance is taking place, it is due not to subsidence of the land, but to erosion of the shores. It is, indeed, the converse of the deposition above mentioned (p. 482) as liable to be mistaken for proof of upheaval. The results of mere erosion by the sea, however, and those of actual depression of the level of the land, cannot always be distinguished without some care. The encroachment of the sea upon the land may involve the disappearance of successive fields, roads, houses, villages, and even whole parishes, without any actual change of level of the land. Certain causes, however, referred to below, may come into operation, producing an actual submergence of land without any real subsidence of the land itself. The following kinds of evidence are usually cited to prove subsidence.

Submerged Forests.—As the land is brought within reach of the waves, and its characteristic surface-features are effaced, the submerged area may retain little or no evidence of its having been a land-surface. It will be covered, as a rule, with sea-worn sand or silt. Hence, no doubt, the reason why, among the marine strata which form so much of the stratified portion of the earth's crust, and contain so many proofs of depression, actual traces of land-surfaces are comparatively rare. It is only under very favorable circumstances, as, for instance, where the area is sheltered from prevalent winds and waves, and where, therefore, the surface of the land can sink tranquilly under the sea, that fragments of that surface may be preserved under overlying marine accumulations. It is in such places that "submerged forests" occur (Fig. 79). These are stumps of trees still in their positions of growth in their native soil, often associated with beds of peat, full of tree-roots, hazel-nuts, branches, leaves, and other indications of a terrestrial surface. There is sometimes, however, considerable risk of deception in regard to the nature and value of such evidence of depression. Where, for instance, shingle or sand is banked up against a shore or river-mouth, considerable spaces may be inclosed and filled with fresh-water, the bottom of which may be some way below high-water mark. In such lagoons terrestrial vegetation and débris from the land

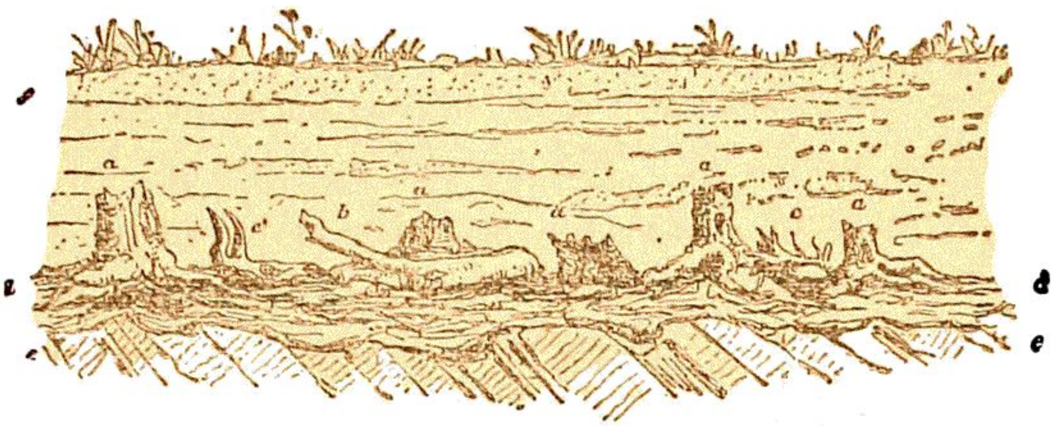

Fig. 79.—Section of Submerged Forest (*B.*).

A platform of older rocks (*e e*) has been covered with soil (*d d*) on which trees (*a a a*) have established themselves. In course of time, after some of the trees had fallen (*b*), and a quantity of vegetable soil had accumulated, inclosing here and there the bones of deer and oxen (*c c*), the area sank, and the sea overflowing it threw down upon its surface sandy or muddy deposits (*f f*).

may be deposited. Eventually, if the protecting barriers should be cut away the tides may flow over the layers of terrestrial peat, giving a false appearance of subsidence. Again, owing to removal of subterranean sandy deposits by springs, overlying peat-beds may sink below sea-level.

De la Beche has described, round the shores of Devon, Cornwall, and western Somerset, a vegetable accumulation, consisting of plants of the same species as those which now grow freely on the adjoining land, and occurring as a bed at the mouths of valleys, at the bottoms of sheltered bays, and in front of and under low tracts of land, of which the seaward side dips beneath the present level of the sea.[218] Over

218 "Geology of Devon and Cornwall," Mem. Geol. Survey. For further accounts of British submerged forests, see Q. J. Geol. Soc. xxii. p. 1.; xxxiv.

this submerged land-surface, sand and silt containing estuarine shells have generally been deposited, whence we may infer that, in the submergence, the valleys first became estuaries, and then sea-bays. If now, in the course of ages, a series of such submerged forests should be formed one over the other, and if, finally, they should, by upheaval of the sea-bottom, be once more laid dry, so as to be capable of examination by boring, well-sinking, or otherwise, they would prove a former long-continued depression, with intervals of rest. These intervals would be marked by the buried forests, and the progress of depression by the strata of sand and mud lying between them. In short, the evidence would be strictly on a parallel with that furnished by a succession of raised beaches as to a former protracted intermittent elevation.

Along the coasts of Holland and the north of France, submerged beds of peat have been regarded as proofs of submergence during historic times. The amount of change varies considerably in different places, and here and there can hardly be appreciated. The sinking during the 350 years preceding 1850 is estimated to have amounted in the polders of Groningen to a mean annual rate of 8 millimetres.[219] In the north of Frânce numerous examples of submerged forests have been observed. In 1846, in digging the harbor of St. Servan, near St. Malo, a Gaulish cemetery containing ornaments and coins, and resting on a still more ancient prehistoric cemetery, was met with at a level of 6 metres below the level of high tide, so that the submergence must have been at least to that extent.[220]

C o r a l-i s l a n d s.—Evidence of widespread depression, over the area of the Pacific and Indian Oceans, has been adduced from the structure and growth of coral-reefs and islands. Mr. Darwin, many years ago, stated his belief that, as the reef-building corals do not live at depths of more than 20 to 30 fathoms, and yet their reefs rise out of deep water, the sites on which they have formed these structures must have subsided, the rate of subsidence being

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p. 447. Geol. Mag. vi. p. 76; vii. p. 64; iii. 2d ser. p. 491; vi. pp. 80, 251. Mr. D. Pidgeon has argued in favor of the submerged forest of Torbay having been formed without subsidence of the land. Quart. Journ. Geol. Soc. xli. (1885), p. 9. See also W. Shone, op. cit. xlviii (1892), p. 96.

219 Lorié, Archives du Musee Teyler, ser. ii. vol. iii. Part 5 (1890), p. 421.

220 Lorié, ibid. p. 438, and papers cited postea, p. 494. But see Suess, "Antlitz der Erde," ii. p. 547.

so slow that the upward growth of the reefs has on the whole kept pace with it.[221] More recent researches, however, show that the phenomena of coral-reefs are in some cases, at least, capable of satisfactory explanation without subsidence, and hence that their existence can no longer be adduced by itself as a demonstration of the subsidence of large areas of the ocean.[222] The formation of coral-reefs is described in Book III. Part II. Section iii., and Mr. Darwin's theory is there more fully explained.

Distribution of plants and animals.—Since the appearance of Edward Forbes's essay upon the connection between the distribution of the existing fauna and flora of the British Isles, and the geological changes which have affected that area,[223] much attention has been given to the evidence furnished by the geographical distribution of plants and animals as to geological revolutions. In some cases, the former existence of land now submerged has been inferred with considerable confidence from the distribution of living organisms, although, as Mr. Wallace has shown in the case of the supposed "Lemuria," some of the inferences have been unfounded and unnecessary.[224] The present distribution of plants and animals is only intelligible in the light of former geological changes. As a single illustration of the kind of reasoning from present zoological groupings as to former geological subsidence, reference may be made to the fact, that while the fishes and mollusks living in the seas on the two sides of the Isthmus of Panama are on the whole very distinct, a few shells and a large number of fishes are identical; whence the inference has been drawn that though a broad water-channel originally separated North and South America in Miocene times, a series of elevations and subsidences has since occurred, the most recent submersion having lasted but a short time, allowing the passage of locomotive fishes, yet not admitting of much change in the comparatively stationary mollusks.[225]

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[221] See Darwin's "Coral Islands," Dana's "Corals and Coral Islands," and the works cited postea, Book III. Part II. Section iii. § 3, under "Coral-reefs." The various theories on the subject are discussed by R. Langenbeck in his "Theorien über die Entstehung der Koralleninseln und Korallenriffe," 1890.

[222] See Proc. Roy. Phys. Soc. Edinburgh, viii. p. 1.

[223] Mem. Geol. Survey, vol. i. 1846, p. 336.

[224] "Island Life," 1880, p. 394. In this work the question of distribution in its geological relations is treated with admirable lucidity and fulness.

[225] A. R. Wallace, "Geographical Distribution of Animals," i. pp. 40, 76.

Fjords.—An interesting proof of an extensive depression of the northwest of Europe is furnished by the fjords or sea-locks by which that region is indented. A fjord is a long, narrow, and often singularly deep inlet of the sea, which terminates inland at the mouth of a glen or valley. The word is Norwegian, and in Norway fjords are characteristically developed. The English word "firth," however, is the same, and the western coasts of the British Isles furnish many excellent examples of fjords, such as the Scottish Loch Hourn, Loch Nevis, Loch Fyne, Gareloch; and the Irish Lough Foyle, Lough Swilly, Bantry Bay, Dunmanus Bay. Similar indentations abound on the west coast of British North America and of the South Island of New Zealand. Some of the Alpine lakes (Lucerne, Garda, Maggiore, and others), as well as many in Britain, are inland examples of fjords.

There can be little doubt that, though now filled with salt water, fjords have been originally land-valleys. The long inlet was first excavated as a valley or glen. The adjacent valley exactly corresponds in form and character with the hollow of the fjord, and must be regarded as merely its inland prolongation. That the glens have been excavated by subaerial agents is a conclusion borne out by a great weight of evidence, which will be detailed in later parts of this work. If, therefore, we admit the subaerial origin of the glen, we must also grant a similar origin to its seaward prolongation. Every fjord will thus mark the site of a submerged valley. This inference is confirmed by the fact that fjords do not, as a rule, occur singly, but, like glens on land, lie in groups; so that, when found intersecting a long line of coast, such as that of the west of Norway or the west of Scotland, they show that the sea now runs far up and fills submerged glens.

Human constructions and historical records.—Should the sea be observed to rise to the level of roads and buildings which it never used to touch, should former half-tide rocks cease to be visible even at low water, and should rocks, previously above the reach of the highest tide, be turned first into shore-reefs, then into skerries and islets, we infer that the coast-line is sinking. Such kind of evidence is found in Scania, the most southerly part of Sweden. Streets, built of course above high-water mark, now lie below it, with older streets lying beneath them, so that the subsidence is of some antiquity. A stone, the position of which had been exactly determined by Linnæus in

1749, was found after 87 years to be 100 feet nearer the water's edge.[226] The west coast of Greenland, for a space of more than 600 miles, is perceptibly sinking. It has there been noticed that, over ancient buildings on low shores, as well as over entire islets, the sea has risen. The Moravian settlers have been more than once driven to shift their boat-poles inland, some of the old poles remaining visible under water.[227] Historical evidence likewise exists of the subsidence of ground in Holland and Belgium.[228] On the coast of Dalmatia, Roman roads and villas are said to be visible below the sea.[229]

§ 3. **Causes of Upheaval and Depression of Land.**—These movements must again be traced back mainly to consequences of the internal heat of the earth. There are various ways in which this cause may have acted. As rocks expand when heated, and contract on cooling, we may suppose that, if the crust underneath a tract of land has its temperature slowly raised, as no doubt takes place round areas of nascent volcanoes, a gradual uprise of the ground above will be the result. The gradual transference of the heat to another quarter may produce a steady subsidence. Basing on the

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[226] According to Erdmann, the subsidence has now ceased, or has even been exchanged for an upward movement (Geol. För. Stockholm Förhandl. i. p. 93). Nathorst also thinks that Scania is now sharing in the general elevation of Scandinavia (ibid. p. 281). It appears that the zero of movement now passes through Bornholm and Laaland.

[227] These observations, which have been accepted for at least a generation past (Proc. Geol. Soc. ii. 1835, p. 208), have recently been called in question, but the alleged disproof is not convincing, and they are here retained as worthy of credence. See Suess, Verhand. Geol. Reichsanstalt, 1880, No. 11, and "Antlitz der Erde," ii. p. 415 *et seq.*

[228] Besides the paper of Lorié, quoted on p. 491, consult Lavaleye, "Affaissement du sol et envasement des fleuves, survenus dans les temps historiques," Brussels, 1859. Grad, Bull. Soc. Geol. France, ii. 3d ser. p. 46. Arends, "Physische Geschichte der Nordseeküste," 1833. Compare also R. A. Peacock on "Physical and Historical Evidences of vast Sinkings of land on the North and West Coasts of France," etc., London, 1868. For submerged peat-beds on French coast, see A. Gaspard, Ann. Soc. Geol. Nord, 1870–74, p. 40. On oscillations of French coast, T. Girard, Bull. Soc. Geograph. Paris, ser. 6, vol. x. p. 225; E. Delfortrie, Act. Soc. Linn. Bordeaux, ser. 4, vol. i. p. 79.

[229] Boll. Com. Geol. Italiano, 1874, p. 57.

calculations of Colonel Totten, cited on p. 508, Lyell estimated that a mass of red sandstone one mile thick, having its temperature augmented 200° Fahr., would raise the overlying rocks 10 feet, and that a portion of the earth's crust of similar character 50 miles thick, with an increase of 600° or 800°, might produce an elevation of 1000 or 1500 feet.[230] But this computation, as Mr. Mellard Reade has pointed out, takes account only of linear expansion. If from any cause the mass of rock whose temperature was augmented could not expand horizontally it would rise vertically, and unless some of the surplus volume could be disposed of by condensation of the rock, the uprise would be three times as much as the linear extension. Taking this view of the case, we find that a mass of the earth's crust twenty miles thick, heated 1000° Fahr., and prevented from extending laterally, would rise 1650 feet.[231]

Again, rocks expand by fusion and contract on solidification. Hence, by the alternate melting and solidifying of subterranean masses, upheaval and depression of the surface may possibly be produced (see pp. 508, 516).

But evidently processes of this nature can only effect changes of level limited in amount and local in area. When we consider the wide tracts over which terrestrial movements are now taking place, or have occurred in past time, the explanation of them must manifestly be sought in some far more widespread and generally effective force in geological dynamics. It must be confessed, however, that no altogether satisfactory solution of the problem has yet been given, and that the subject still remains beset with many difficulties.

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230 "Principles," ii. p. 235.

231 Mellard Reade, "Origin of Mountain Ranges" (1886), pp. 112, 114.

Professor Darwin, in one of his memoirs already cited (*ante*, p. 46), has suggested a possible determining cause of the larger features of the earth's surface. Assuming for his theory a certain degree of viscosity in the earth, he points out that, under the combined influence of rotation and the moon's attraction, the polar regions tend to outstrip the equator, and to acquire a consequent slow motion from west to east relatively to the equator. The amount of distortion produced by this screwing motion he finds to have been so slow, that 45,000,000 years ago, a point in lat. 30° would have been $4\frac{3}{4}'$, and a point in lat. 60° $14\frac{1}{4}'$ further west, with reference to the equator, than they are at present. This slight transference shows us, he remarks, that the amount of distortion of the surface strata from this cause must be exceedingly minute. But it is conceivable that, in earlier conditions of the planet, this screwing action of the earth may have had some influence in determining the surface features of the planet. In a body not perfectly homogeneous it might originate wrinkles at the surface running perpendicular to the direction of greatest pressure. "In the case of the earth, the wrinkles would run north and south at the equator, and would bear away to the eastward in northerly and southerly latitudes, so that at the north pole the trend would be northeast, and at the south pole northwest. Also the intensity of the wrinkling force varies as the square of the cosine of the latitude, and is thus greatest at the equator and zero at the poles. Any wrinkle, when once formed, would have a tendency to turn slightly, so as to become more nearly east and west than it was when first made."

According to the theory, the highest elevations of the earth's surface should be equatorial, and should have a general north and south trend, while in the northern hemisphere the main direction of the masses of land should bend round toward northeast, and in the opposite hemisphere toward southeast. Prof. Darwin thinks that the general facts of terrestrial geography tend to corroborate his theoretical views, though he admits that some are very unfavorable to them. In the discussion of such a theory, however, we must remember that the present mountain-chains on the earth's surface are not aboriginal, but arose at many successive and widely-separated epochs. Now it is quite certain that the younger mountain-chains (and these include the loftiest on the surface of the globe) arose, or at least received their chief upheaval, during the Tertiary periods—a comparatively late date in geological history. Unless we are to enlarge enormously the limits of time which physicists are willing to concede for the evolution of the whole of that history, we can hardly suppose that the elevation of the great mountain-chains took place at an epoch at all approaching an antiquity of 45,000,000 years. Yet, according to Prof. Darwin's showing, the superficial effects of internal distortion must have been exceedingly minute during the past 45,000,000 years. We must either therefore multiply enormously the periods required for geological changes, or find some cause which could have elevated great mountain-chains at more recent intervals.

But it is well worth consideration whether the cause suggested by Prof. Darwin may not have given their initial trend to the masses of land, so that any subsequent wrinkling of the terrestrial surface, due to any other cause, would be apt to take place along the original lines. To be able to answer this question, it is necessary to ascertain the dominant line of strike of the older geological formations. But information on this subject is still scanty. In Western Europe, the prevalent line along which terrestrial plications took place during Palæozoic time was certainly from S.W. or S.S.W. to N.E. or N.N.E., and the same direction is recognizable in the eastern States of North America. But the trend of later formations is more varied. The striking contradictions between the actual direction of so many mountain-chains and masses of land, and what ought to be their line according to the theory, seem to indicate that while the effects of internal distortion may have given the first outlines to the land-areas of the globe, some other cause has been at work in later times, acting sometimes along the original lines, sometimes across them.

The main cause to which geologists are now disposed to refer the corrugations of the earth's surface is secular cooling and consequent contraction.[232] If our planet has been steadily losing heat by radiation into space, it must have progressively diminished in volume. The cooling implies contraction. According to Mallet, the diameter of the earth is less by at least 189 miles since the time when the planet was a mass of liquid.[233] But the contraction has not manifested itself uniformly over the whole surface of the planet. The crust varies much in structure, in thermal resistance, and in the position of its isogeothermal lines. As the hotter nucleus contracts more rapidly by cooling than the cooled and hardened crust, the latter must sink down by its own weight, and in so doing requires to accommodate itself to a continually diminishing

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[232] For an able criticism of this view see Fisher's "Physics of Earth's Crust," 2d Edit. Consult also Mr. Reade's "Origin of Mountain Ranges."

[233] Phil. Trans. 1873, p. 205.

diameter. The descent of the crust gives rise to enormous tangential pressures. The rocks are crushed, crumpled, and broken in many places. Subsidence must have been the general rule, but every subsidence would doubtless be accompanied with upheavals of a more limited kind. The direction of these upheaved tracts, whether determined, as Prof. Darwin suggests, by the effects of internal distortion, or by some original features in the structure of the crust, would be apt to be linear. The lines, once taken as lines of weakness or relief from the intense strain, would probably be made use of again and again at successive paroxysms or more tranquil periods of contraction. Mallet ingeniously connected these movements with the linear direction of mountain-chains, volcanic vents, and earthquake shocks. If the initial trend to the land-masses were given as hypothetically stated by Prof. Darwin, we may conceive that after the outer parts of the globe had attained a considerable rigidity and could then be only slightly influenced by internal distortion, the effects of continued secular contraction would be seen in the intermittent subsidence of the oceanic basins already existing, and in the successive crumpling and elevation of the intervening stiffened terrestrial ridges.

This view, variously modified, has been widely accepted by geologists as furnishing an explanation of the origin of the upheavals and subsidences of which the earth's crust contains such a long record. But it is not unattended with objections. The difficulty of conceiving that a globe possessing on the whole a rigidity equal to that of glass or steel could be corrugated as the crust of the earth has been, has led some writers to adopt the hypothesis already described (*ante*, p. 105), of an intermediate viscous layer between the solid crust and the solid nucleus, while others have suggested that the observed subsidence may have been caused, or at least aggravated, by the escape of vapors from volcanic orifices. But with modifications, the main cause of terrestrial movements is still sought in secular contraction.

Some observers, following an original suggestion of Babbage,[224] have supposed that upheaval and subsidence, together with the solidification, crystallization, and metamorphism of the layers of the earth's crust, may have been in large measure due to the deposition and removal of mineral matter on the surface. There can be no doubt that the lines of equal internal temperature (isogeothermal lines) for a considerable depth downward, follow approximately the contours of the surface, curving up and down as the surface rises into mountains or sinks into plains. The deposition of a thousand feet of rock will, of course, cause a corresponding rise in the isogeotherms, and if we assume the average rise of temperature to be 1° Fahr. for every 50 feet, then the temperature of the crust immediately below this deposited mass of rock will be raised 20°. But masses of sediment of much greater thickness have been laid down, and we may admit that a much greater increase of temperature than 20° has been effected by this means. On the other hand, the denudation of the land must lead to a depression of the isogeotherms, and a consequent cooling of the upper layers of the crust.

It may be conceded that in so far as the internal structure of rocks may be modified by such progressive increase of temperature as would arise from superficial deposit, this

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[224] Journ. Geol. Soc. iii. (1834), p. 206.

cause of change must have a place in geological dynamics. But it has been urged that besides this effect, the removal of rock by denudation from one area and its accumulation upon another affects the equilibrium of the crust; that the portions where denudation is active, being relieved of weight, rise, while those where deposition is prolonged, being on the contrary loaded, sink.[235] This hypothesis has recently been strongly advocated by some of the geologists who have been exploring the Western Territories of America, and who point in proof of its truth to evidence of continuous subsidence in tracts where there was prolonged deposition, and of the uprise and curvature of originally horizontal strata over mountain ranges like the Uinta Mountains in Wyoming and Utah, which have been for a long time out of water. To suppose, however, that the removal and deposit of a few thousand feet of rock should so seriously affect the equilibrium of the crust as to cause it to sink and rise in proportion, would evince such a mobility in the earth as could not fail to manifest itself in a far more powerful way under the influence of lunar and solar attraction. That there has always been the closest relation between upheaval and denudation on the one hand, and subsidence and deposition on the other, is undoubtedly true. But denudation has been one of the consequences of upheaval, and deposition has been kept up only by continual subsidence.

We are concerned in the present part of this work only with the surface features of the land in so far as they

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[235] Similarly it has been contended that the accumulation of a massive ice-sheet on the land would cause a depression of the terrestrial surface. N. S. Shaler, Proc. Boston Nat. Hist. Soc. xvii. p. 288. T. F. Jamieson, Quart. Journ. Geol. Soc. 1882, and Geol. Mag. 1882, pp. 400, 526. Fisher, "Physics of Earth's Crust," p. 223.

bear on questions of geological dynamics. The history of these features will be more conveniently treated in Book VII. after the structure and history of the crust have been described. Before quitting the subject, however, we may observe that the larger terrestrial features, such as the great ocean basins, the lines of submarine ridge surmounted here and there by islands chiefly of volcanic materials, the continental masses of land, and at least the cores of most great mountain-chains, are in the main of high antiquity, stamped as it were from the earliest geological ages on the physiognomy of the globe, and that their present aspect has been the result not merely of original hypogene operations, but of long-continued superficial action by the epigene forces described in Book III. Part II.

END OF FIRST PART OF "TEXT-BOOK OF GEOLOGY"