

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 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 would largely depend upon the original structure of the crust. It would be apt to occur in lines which, 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. Mr Mallet, in the paper already cited, has ingeniously connected these movements with the linear direction of mountain chains, volcanic vents, and earthquake shocks.

Though the origin of the present surface configuration of the land will be more conveniently discussed in a subsequent part of this article, after the structure of the earth's crust has been described, a few words may be inserted here, where some allusion to the subject might be looked for. Mountains may arise from three causes—(1) from the corrugation of the earth's crust due to the effects of secular contraction; (2) from the accumulation of materials poured out of volcanic orifices; and (3) from the isolation of elevated masses of ground, owing to the removal, by denudation, of the materials originally connecting them, and to the consequent formation of valleys. Mountains formed in the volcanic way are almost always conical, and are either solitary, as Etna, or occur in linear groups, like the volcanoes of Java. Those formed by denudation are of minor dimensions, and rather deserve the name of hills. Mountain-chains, on the other hand, which are the dominant features of the earth's surface, though they may have lines of volcanic vents along their crests, are not formed essentially of volcanic materials, but of the sedimentary and crystalline rocks of the crust which have been ridged up into vast folds. If the continental lands may be compared to great undulations of the solid surface of the globe, the mountain-chains may be likened to the breaking crests of such wave-like undulations. In their internal structure mountain-chains bear witness to the intense crumpling of the rocks during the process of upheaval. As a consequence of the uprise of two or more parallel ranges of mountain, lines of longitudinal valley must be produced. But no sooner is a mass of land raised above the sea than it is exposed to the attacks of air, rain, frost, springs, glaciers, or other meteoric agents of disintegration. Its surface is then worn down, the flow of water down its slopes cuts out gulleys, ravines, and valleys, so that eventually a very rugged surface is produced, on which, probably, no portion of the original surface of upheaval may remain, but where new lines of minor ridge and valley may appear as the combined result of internal geological structure and atmospheric denudation. The reader, however, is referred to part vii. of this article for a fuller treatment of this interesting subject.

During the movements by which mountain masses have been upheaved, the stratified rocks have been so compressed as to occupy, in many cases, but a small proportion of the horizontal extent over which they originally extended. They have adjusted themselves to this diminished area by undergoing intense plication, and thus acquiring a much greater vertical depth. On the other hand, they have been abundantly fractured, some portions of their mass being pushed up, others being let down, so that the crust is

traversed with a kind of complicated network of fissures. The discussion of these features of geological structure, however, must likewise be postponed to part iv., where the facts regarding their occurrence will be described.

Section IV.—Hypogene Causes of Changes in the Texture, Structure, and Composition of Rocks.

The phenomena of hypogene action hitherto under consideration have related almost wholly to the effects produced at the surface. It is evident, however, that these phenomena must be accompanied by very considerable changes in the rocks which form the earth's outer crust. These rocks, as just stated, have been subjected to enormous pressure; they have been contorted, crumpled, and folded back upon themselves, as if thousands of feet of solid limestones, sandstones, and shales had been merely a few layers of carpet; they have been shattered and fractured everywhere; they have in one place been pushed far above their original position, in another depressed far beneath it; so great has been the compression which they have undergone that their component particles have in many places been rearranged, and even crystallized. They have here and there actually been reduced to fusion, and have been abundantly invaded by masses of molten rock from below.

In the present section of this article we shall consider chiefly the nature of the agencies by which such changes have been effected; the results achieved, in so far as they constitute part of the architecture or structure of the earth's crust, will be discussed in part iv. At the outset, it is evident that we can hardly hope to detect many of these processes of subterranean change actually in progress and watch their effects. The very vastness of some of them places them beyond our direct reach, and we can only reason regarding them from the changes which we see them to have produced. But a good number are of a kind which we can in some measure imitate in our laboratories and furnaces. It is not requisite, therefore, to speculate wholly in the dark on this subject. Since the original and classic researches of Sir James Hall, the founder of experimental geology, great progress has been made in the investigation of hypogene processes by experiment. The conditions of nature have been imitated as closely as possible, and varied in different ways, with the result of giving us an increasingly clear insight into the physics and chemistry of subterranean geological changes. The succeeding portions of this section of the article will therefore be chiefly devoted to an illustration of the nature of hypogene action, in so far as that can be inferred from the results of actual experiment. The subject may be conveniently treated under three heads—(1) the effects of heat; (2) the effects of pressure and contraction; (3) the influence of water in effecting changes in minerals and rocks.

§ 1. Effects of Heat.

The importance of heat among the transformations of the rocks has been fully admitted by geologists, since it used to be the watchword of the Huttonian or Vulcanist school at the end of last century. Two sources of subterranean heat may have at different times and in different degrees co-operated in the production of hypogene changes—(1) the internal heat of the globe, of which some account has already been given, and (2) the heat due to the transformation of mechanical energy in the crumpling, fracturing, and crushing of the rocks of the crust, as these have been from time to time compelled to adjust themselves to the diminishing diameter of the more rapidly cooling and contracting interior. From which of these two sources, or from what combination of them, the heat was derived by which any given change in the rocks was produced, is a problem which admits

in the meantime of only very partial solution. Leaving this question for the present, let us examine the effects which are clearly referable to the influence of heat. It is evident that the conditions under which these effects are produced must vary almost infinitely. We have to consider (1) the temperature, from the lowest at which any change is possible up to that of complete fusion; (2) the nature of the rock operated upon, some materials being much more susceptible of change from heat than others; (3) the pressure under which the heat acts, the potency of this agency being much increased with increase of pressure; (4) the presence of water, whereby chemical changes take place which would not be possible in dry heat.

In an interesting series of experiments the illustrious De Saussure (1779) fused some of the rocks of Switzerland and France, and inferred from them, contrary to the opinion previously expressed by Desmarest,¹ that basalt and lava have not been produced from granite, but from hornstone (pierre de corne), varieties of "schorl," calcareous clays, marls, and micaceous earths, and the cellular varieties from different kinds of slate.² He observed, however, that the artificial products obtained by fusion were glassy and enamel-like, and did not always recall volcanic rocks, though some exactly resembled porous lavas.

Sir James Hall, about the year 1790, began an important investigation, in which he succeeded in reducing various ancient and modern volcanic rocks to the condition of glass, and in restoring them, by slow cooling, to a stony state. Since that time many other researches of a more complicated kind have been undertaken, especially by Delesse, Daubrée, Deville, Bunsen, Bischof, H. and W. Rogers. By these observations it has been abundantly proved that all rocks undergo molecular changes when exposed to high temperature, that when the heat is sufficiently raised they become fluid, that if the glass thus obtained is rapidly cooled it remains vitreous, and that, if allowed to cool slowly, a more or less distinct crystallization sets in, the glass is devitrified, and a lithoid product is the result.

Illustrations of the influence of different degrees of heat upon rocks of different kinds may often be very instructively observed at lime-kilns, especially those roughly-built kilns or pits which may still be met with in outlying districts. Some of the stones lining such cavities will be found with no sensible change, others show a somewhat cellular texture, others have acquired a rudely prismatic structure, while some have had their surfaces fused into a rough glaze or enamel. The bricks or stones used for lining furnaces present similar illustrations, the columnar or prismatic structure being occasionally very perfectly developed in these materials. Mere contact with a highly-heated surface, and subsequent gradual cooling, have often produced this prismatic arrangement in rocks of the most diverse kinds. Thus, in Scotland, beds of sandstone and seams of coal have acquired the most perfect prismatic structure from the intrusion of basalt dykes or sheets through them. To these and other effects of intruded igneous rocks reference will be made in the sequel. In these cases the alteration is merely local, and has obviously been produced by contact with a highly heated surface. But, besides such minor effects due merely to contact, others of a more general kind affect large masses of rock or whole districts of country.

When rocks are exposed to temperatures as high as their melting-points, they fuse into glass which, in the great majority of cases, is of a bottle-green or black colour, the depth of the tint depending mainly on the proportion of iron. In this respect they resemble the natural glasses—pitchstones and obsidians. They almost always contain

minute cells or bubbles, arising probably from the disengagement of water or of oxygen during the fusion. But after the most thorough fusion which has been found possible, minute granules usually appear in the solidified glass. Sometimes these consist of specks of quartz, which is especially apt to remain unmelted when the rock is very siliceous, or of other minerals of the original rock. But a microscopic investigation of fused rocks shows that, even in what seems to be a tolerably homogeneous glass, there are abundant minute hair-like, feathered, needle-shaped, or irregularly-aggregated bodies diffused through the glassy paste. These *crystallites* are in some cases colourless silicates, in others they are opaque metallic oxides, particularly oxides of iron. They precisely resemble the crystallites which are observed in many volcanic rocks, such as obsidian, pitchstone, and basalt. They may be obtained even from the fusion of a granitic or granitoid rock, as in the well-known case of the Mount Sorrel syenite near Leicester, which, being fused and slowly cooled, yielded abundant crystallites, including exquisitely grouped octohedra of magnetite.

According to the observations of Delesse, volcanic rocks, when reduced to a molten condition, attack briskly the sides of the Hessian crucibles in which they are contained, and even eat them through. This is an interesting fact, for it helps to explain how some intrusive igneous rocks have come to occupy positions previously filled by sedimentary strata, and why, under such circumstances, the composition of the same mass of rock should be found to vary considerably from place to place.³

It would appear that, in passing from a crystalline into a vitreous condition, rocks undergo a diminution of density, which, on the whole, is greater the more silica and alkali are present, and is less as the proportion of iron, lime, and alumina increases. According to Delesse, granites, quartziferous porphyries, and such highly silicated rocks lose from 8 to 11 per cent. of their density when they are reduced to the condition of glass, basalts lose from 3 to 5 per cent., and lavas, including the vitreous varieties, from 0 to 4 per cent. This diminution of density (and consequent increase of volume) may account for minor oscillations of the ground so often observed in volcanic regions. If we suppose a subterranean mass of lava 500 feet thick to pass from the fluid to the crystalline condition, this might cause a subsidence of the ground above to the extent of about 20 or 25 feet. The transition of a similar mass of rock from the solid to the fluid condition would cause an uprise to a like amount.

So far as experiments have yet been conducted, it has been found impossible to obtain from a piece of fused rock a crystalline substance exactly resembling the original mass. Externally it may appear quite stony, but its internal structure, as revealed by the microscope, shows it to be essentially a slag or glass, and not a truly crystalline rock. There is another fundamental difference between the natural and artificial products. When a compound containing substances of different fusibilities is artificially melted, and allowed thereafter to cool in such a way that the various ingredients may separate from each other, they appear in their order of fusibility, the most refractory coming first, and the most fusible being the last to take a solid form. But in rocks which have crystallized naturally from a fluid condition, it is often to be observed that the component minerals have been far from obeying what might have been supposed to be their invariable law. Thus, in all parts of the world, granite presents the very striking fact that its quartz, which we call an infusible mineral, has actually solidified after the more fusible felspar. In the Vesuvian lavas the

¹ Mem. Acad. Scienc., 1771, p. 273.

² De Saussure, *Voyages dans les Alpes*, edit. 1803, tome i. p. 178.

³ Bull. Soc. Géol. France, 2d ser., iv. 1352.

difficultly fusible leucite may be seen to have enclosed crystals already formed of the fusible augite. In many ancient crystalline rocks the pyroxenic constituents, which offer a less resistance to fusion, have assumed a crystalline form before the more refractory triclinic felspars. From these facts it is clear that, in the fusion of rocks and in their subsequent consolidation, there must have been conditions under which the normal order of appearance of the minerals was disturbed or reversed. Yet another fact may be mentioned to show further the difference between the kind of fusion which has frequently obtained in nature and that of the ordinary operations of a glass-work or iron-furnace. As far back as the year 1846 Scheerer showed that there exist in granite various minerals which could not have consolidated save at a comparatively low temperature. He instanced especially several gadolinites, orthites, and allanites, which cannot endure a higher temperature than a dull-red heat without altering their physical characters; and he concluded that granite, though it may have possessed a high temperature, cannot have solidified from simple igneous fusion.

We may conclude, therefore, that the manner in which rocks have been melted within the crust is not that mere simple fusion which we can accomplish artificially, but that it has involved conditions which have not been successfully imitated in any laboratory or furnace. Two obvious differences must occur to the reader between the natural and artificial operations. In the first place, rocks which have undoubtedly once been in a fluid or at least pasty condition, and which have been injected as veins and dykes into previously consolidated masses, contain water imprisoned within their component crystals. This is not water which has been subsequently introduced. It is contained in minute cells, which it usually does not now completely fill, but which it no doubt did occupy completely at the time and temperature at which the rock was consolidated. We have seen (*ante*, p. 250) how abundant are the discharges of water-vapour from volcanic fires, how the molten lava-streams issue from their vents, saturated, as it were, with steam, and how the steam continues to rise from them long after they have congealed and come to rest. In the solid crystals of lava which were erupted only recently, as well as in those of early geological periods, the presence of water in minute cavities may be readily detected. It is in the quartz of such rocks, and still more in that of granite, that the detection of water-cavities is most easily made. The quartz of granite is usually full of them. "A thousand millions," says Mr J. Clifton Ward, "might easily be contained within a cubic inch of quartz, and sometimes the contained water must make up at least 5 per cent. of the whole volume of the containing quartz." Thus microscopic investigation confirms the conclusion arrived at by Scheerer in the memoir already cited, that at the time of its eruption granite must have been a kind of pasty mass containing a considerable proportion of water. It is common now to speak of the "aquo-igneous" origin of some eruptive rocks, and to treat their production as a part of what is termed the "hydro-thermal" operations of geology. We may conclude that, while some rocks, like obsidian and pitchstone, which so closely resemble artificial glasses, may have been derived from a simple igneous fusion—such as can be imitated in a furnace (though even in these the presence and influence of water may be traced), the great majority of rocks have had a more complex origin, and in a great number of cases can be proved to have been mingled with more or less water while they were still fluid.

In the second place, there can be no question that, in the great hypogene laboratory of nature, rocks have been softened and fused under enormous pressure. Besides the pressure due to their varying depth from the surface, they

must have been subject to the enormous expansion of the superheated water or vapour which filled all their cavities. Mr Sorby has ingeniously estimated the probable pressure under which granite consolidated by taking the ratio between the size of the liquid cavities in the quartz and that of the contained bubble or vacuity. Assuming the temperature of consolidation to have been 680° Fahr. (360° Cent.), or a dull-red heat, he inferred that in many cases the pressure under which the granite consolidates must have been equal to that of an overlying mass of rock 50,000 feet, or more than 9 miles, in thickness. It is not probable that any such thick overlying mass ever did cover the granite; the pressure, even if it be allowed to have been so great, must have been due partly to other causes, such as the compression due to secular contraction.

It would appear therefore that perfect anhydrous fusion, or the reduction of a rock to the state of a completely homogeneous glass, has been a comparatively rare process in nature, or at least that such glasses, if originally formed, have in the vast majority of cases undergone devitrification and crystallization, until the glassy base has been reduced to a smaller or larger fraction of the total mass of the rock, or has entirely passed into a stony condition. In many volcanic rocks the original vitreous base or ground-mass can be readily observed with the microscope between the definitely-formed crystals. Crystallites, or arrested stages in the crystallization of iron oxides and of silicates, can often be detected in these rocks, more especially where it is evident that they must have cooled with comparative rapidity, as where they have been thrust into narrow fissures to form dykes. But in rocks such as granite, where no glass exists, but where the mineral constituents are all crystalline, no trace of the crystallites occurs. Doubtless such differences point to original distinctions in the kind and degree of fusion of the rocks. It seems reasonable to suppose that those rocks which show a glassy ground-mass, and the presence of crystallites, have been fused under conditions more nearly resembling those of the simple igneous fusion of experiment.

It has long been known that many mineral substances can be obtained in a crystalline form from the condensation of vapours. This process, called sublimation, may be the result of the mere cooling and reappearance of bodies which have been vaporized by heat and solidify on cooling, or from the solution of these bodies in other vapours or gases, or from the reaction of different vapours upon each other. These operations are of common occurrence at volcanic vents, and in the crevices of recently erupted and still hot lava-streams. They have been successfully imitated by experiment. In the early researches of Sir James Hall on the effects of heat modified by compression, he obtained by sublimation "transparent and well-defined crystals," lining the unoccupied portion of a hermetically-sealed iron tube, in which he had placed and exposed to a high temperature some fragments of limestone (*Trans. Roy. Soc. Edin.*, vi. 110). Numerous experiments have been made by Messrs Delesse, Daubrée, and others, in the production of minerals by sublimation. Thus many of the metallic sulphides found in mineral veins have been produced by exposing to a comparatively low temperature (between that of boiling water and a dull-red heat) tubes containing metallic chlorides and sulphide of hydrogen. By varying the materials employed, corundum, quartz, apatite, and other minerals have been obtained. It is not difficult, therefore, to understand how, in the crevices of lava-streams and volcanic cones, as well as in some mineral veins, sulphides and oxides of iron and other minerals may have been formed by the ascent of heated vapours. Superheated steam is endowed with a remarkable power of dissolving that intractable substance, silica; artificially heated to the tem-

perature of the melting point of cast-iron, it rapidly attacks silica, and deposits the mineral in snow-white crystals as it cools.

§ 2. Effects of Pressure and Contraction.

Besides the influence of pressure in raising the melting point of subterranean rocks, and in permitting water to remain fluid among them at temperatures far above the boiling-point, even at a red or perhaps a white heat, we have to consider the effects produced by the same cause upon rocks already solidified. The simplest and most obvious result of pressure upon such rocks is their consolidation, as where a mass of loose sand is gradually compacted into a more or less coherent stone, or where a layer of vegetation is compressed into peat, lignite, or coal. In many cases the cohesion of a sedimentary rock is due merely to the pressure of the superincumbent strata. But it usually happens that some cementing material has contributed to bind the component particles together. Of these natural cements the most frequent are peroxide of iron, silica, and carbonate of lime.

Pressure equally distributed over a rock presenting everywhere nearly the same amount of resistance will promote consolidation, but may produce no further internal change. If, however, the pressure becomes extremely unequal, or if the rock subjected to it can find escape from the influence in one or more directions, there will be a disturbance or rearrangement of the particles, which by this means are made to move upon each other. Five consequences of these movements may be noticed here.

(1) *Cleavage*.—When a mass of rock, owing to subsidence or any other cause, is subjected to powerful lateral compression, its innate particles, which in all rocks have almost invariably a longer and shorter axis, tend, under the intense strain, to rearrange themselves in the line of least resistance, that is, with their long axes perpendicular to the direction of the pressure. The result of this readjustment is that the rock affected by it acquires a facility for splitting along the lines in which its component particles have placed themselves. Fine-grained argillaceous rocks show most characteristically this internal change; but in coarse materials it becomes less conspicuous, or even disappears. Rocks which have been thus acted on, and have acquired this superinduced fissility, are said to be *cleaved*, and the fissile structure is termed *cleavage*. This has been proved experimentally by Sorby, who produced perfect cleavage in pipeclay through which scales of oxide of iron had previously been mixed. Dr Tyndall superinduced cleavage on bees-wax and other substances by subjecting them to severe pressure. Cleavage among rocks occurs on a great scale in countries where the strata have been greatly plicated, that is, where they now occupy much less horizontal surface than they once did, and consequently where, in accommodating themselves to their diminished area, they have had to undergo much powerful lateral compression. The structure of districts with cleaved rocks is described in part iv.

(2) Further evidence of the compression to which rocks have been subjected is furnished by the way in which contiguous pebbles in a conglomerate may be found to have been squeezed into each other, and even sometimes to have been elongated in a certain general direction. It is doubtless the coarseness of the grain of such rocks which permits the effects of compression to be so readily seen. Similar effects must take place in fine-grained rocks, though they escape observation. Organic remains both of plants and animals may often be found to have undergone considerable distortion from this cause. M. Daubrée has imitated experimentally the indentations produced by the contiguous portions of conglomerate pebbles.¹

¹ *Comptes Rendus*, xlv. 823.

(3.) The ingenious experiments of M. Tresca on the flow of solids have proved that, even at ordinary atmospheric temperatures, solid resisting bodies like lead, cast-iron, and ice, may be so compressed as to undergo an internal motion of their parts which is closely analogous to that of fluids. Thus, a solid jet of lead has been produced by placing a piece of the metal in a cavity between the jaws of a powerful compressing machine. Iron, in like manner, has been forced to flow in the solid state into cavities and take their shape. On cutting sections of the metals so compressed, their particles or crystals are found to have ranged themselves in lines of flow which follow the contour of the space into which they have been squeezed. Such experiments are of considerable geological interest, for they show that in certain circumstances, under great pressure, the unequally mixed particles of rocks within the earth's crust may have been forced to move upon each other, and thus to acquire a "fluid-structure" resembling that which is seen in rocks which have possessed true liquidity. No large sheet of rock can be expected, however, to have undergone this internal change; the effects could only be produced exceptionally at places where there was an escape from the pressure as, for instance, along the sides of fissures, or in other cavities of rocks. The explanation cannot be applied to the case of rocks like schists, which display a kind of rude foliation or fluid-structure over areas many thousands of square miles in extent.

(4) *Plication*.—Reference has already been made to the fact that, owing to the more rapid contraction of the inner portion of the globe, the outer layer or crust is from time to time forced to adjust itself to this change by subsiding. As a consequence of the subsidence, the descending area requires to occupy less horizontal space, and must therefore suffer powerful lateral compression. The rocks are thus crumpled up, as, in the classic experiment of Sir James Hall, folds of cloth are folded when a weight is placed upon them and they are squeezed from either side. The mere subsidence of such a curved surface as that of our globe must thus necessarily produce much lateral compression. Mr J. M. Wilson has calculated that, if a tract of the earth's surface, 345 miles in breadth, be depressed one mile, it will undergo compression to the extent of 121 yards; at two miles the compression will be 189 yards; at eight miles 598 yards. The observed amount of compression in districts of contorted rocks, however, far exceeds these figures. Another cause of the compression and contortion of rocks is the injection into them of igneous masses from below, but this is probably a minor source of disturbance. The character of plicated rocks is described in part iv. p. 300.

(5) *Faults*.—Closely connected with the disturbances which have produced contortions come those by which the crust of the earth has been fractured. But in this case the movement is one of elevation rather than of subsidence; for, instead of having to occupy a diminished diameter, the rocks get more room by being pushed up, and as they cannot occupy the additional space by any elastic expansion of their mass, they can only accommodate themselves to the new position by a series of dislocations. Some portions will be pushed up farther than others, and this will happen more particularly to those which have a broad base. These will rise more than those with narrow bottoms, or the latter will seem to sink relatively to the former. Each broad-bottomed segment will thus be bounded by two sides sloping towards the upper part of the block. This is found to be almost invariably the case in nature. A fault or dislocation is nearly always inclined from the vertical, and the side to which the inclination rises, and from which it "hades," is the upthrow side. The details of these features of geological structure are discussed in part iv., section v.

§ 3. Influence of Water.

In the great geological contest fought at the beginning of the century between the Neptunists and the Plutonists, the two great battle-cries were, on the one side, Water, on the other, Fire. The progress of the science since that time has shown that each of the parties had truth on its side, and had seized one aspect of the problems touching the origin of rocks. If subterranean heat has played a large part in the construction of the materials of the earth's crust, water, on the other hand, has performed a hardly less important share of the task. They have often co-operated together, and in such a way that the result must be regarded as their joint achievement, wherein the respective share of each can hardly be exactly apportioned. In the following brief *résumé* of this subject we shall consider the changes produced by pure water, by water charged with substances in solution, and by water raised above ordinary temperatures.

By numerous observations it has been proved that all rocks within the accessible portion of the earth's crust contain interstitial water, or, as it is sometimes called, quarry-water (*eau-de-carrière*). This is not chemically combined with their mineral constituents, but merely retained in their pores. Most of it evaporates when the stone is taken out of the parent rock and freely exposed to the atmosphere. The absorbent powers of rocks vary greatly, and chiefly in proportion to their degree of porosity. Gypsum absorbs from about 0.50 to 1.50 per cent. of water by weight; granite, about 0.37 per cent.; quartz from a vein in granite, 0.08; chalk, about 20.0; plastic clay, from 19.5 to 24.5. These amounts may be increased by exhausting the air from the specimens and then immersing them in water.

The water enclosed within the interstices and crystals of igneous rocks may be either an original constituent, deriving its origin, like any of the component minerals, from molten reservoirs within the earth's crust, or it may have descended from the surface to the incandescent rocks. Many facts may be adduced in support of the greater probability of the second view. Besides the general proximity of volcanic orifices to large sheets of water, we have abundant evidence of the actual descent of water from the surface, both through fissures, and also by permeation through the solid substance of rocks. All surface rocks contain water, and no mineral substance is strictly impervious to the passage of liquid. The well-known artificial colouring of agates proves that even the mineral substances apparently most homogeneous and impervious can be traversed by liquids. M. Daubrée has instituted a series of experiments to illustrate the power possessed by water of penetrating rocks, in virtue of their porosity and capillarity, even against a considerable counter-pressure of vapour; and, without denying the presence of original water, he concludes that the interstitial water of igneous rocks may all have been derived by descent from the surface.

The presence of interstitial water must affect the chemical constitution of rocks. It is now well understood that there is probably no terrestrial substance which, under proper conditions, is not to some extent soluble in water. By an interesting series of experiments, made many years ago by Messrs Rogers, it was ascertained that many of the ordinary mineral constituents of rocks could be dissolved to an appreciable extent even by pure water, and that the change was accelerated and augmented by the presence of carbonic acid.¹ Silica, alkaliferous silicates, and iron oxides can be taken up and held in solution by pure water, even at ordinary temperatures, in considerable quantities.

¹ *American Journ. Science* (2), v. 401.

The mere presence of pure water therefore within the pores in subterranean rocks cannot but give rise to changes in the combustion of these rocks. Some of the more soluble materials must be dissolved, and, as the water evaporates, must be redeposited in a new form.

But water in a natural state is never chemically pure. In its descent through the air it absorbs oxygen and carbonic acid, besides other impurities (see p. 267), and as it filters through the soil it abstracts more carbonic acid, as well as other results of decomposing organic matter. It is thus enabled to effect numerous decompositions of the rocks underneath. The nature of these changes may be inferred from the composition of spring water, to which reference will subsequently be made (p. 270). For the present it will be sufficient to remark that two important kinds of chemical decomposition must evidently arise from the action of such infiltrating water. (1.) The presence of the organic matter must exercise a reducing power on oxides. This will be more especially the case with those of iron, the nearly insoluble hæmatite being reduced to the protoxide, which, converted into carbonate, is readily removable in solution. There can be little doubt that by this means a vast amount of ferruginous matter is extracted from subterranean rocks and carried to the surface. (2.) The presence of carbonic acid enables the water to attack vigorously the mineral constituents of rocks. Alkaline carbonates, with carbonates of lime and magnesia, and protoxides of iron and manganese, are produced, and these substances borne onward in solution give rise to further reactions among the rocks through which they are carried. "In the decomposition of rocks," says Bischof, "carbonic acid, bicarbonate of lime, and the alkaline carbonates bring about most of the decompositions and changes in the mineral kingdom."

The microscopic study of rocks has thrown much light upon the mineralogical alterations in rocks due to the influence of percolating water. Even the most solid-looking, unweathered rocks, are found to have been affected by such metamorphism. Their hydrous magnesian silicates, for example, are partially or wholly converted into such hydrous forms as serpentine, chlorite, or delessite. The process of conversion may often be watched. It can be seen to have advanced along the fissures or cleavage-planes of the minerals leaving the intervening sections still fresh; or it may be observed to have proceeded in such a way that diffused alteration-products are dispersed in filaments or irregular patches through the base of the rock, or gathered together and even recrystallized in cavities; or the whole rock, as in many serpentines, has undergone an entire transformation. Much information regarding such internal alterations of rocks may be obtained from the study of *pseudomorphs*, that is, crystals having the external form of the mineral of which they originally consisted, with the internal structure and composition of the mineral which has replaced it. Serpentine representing olivine, clay taking the place of rock-salt, silica that of wood, and marcasite that of molluscan shell, are familiar examples. There is no reason to doubt that these changes may, in the course of ages, have been effected at ordinary temperatures by water descending from the surface of the ground.

But two other considerations require to be taken into account in the discussion of the internal transformations of rocks by subterranean water. (1.) In the first place, the water has often been at a high temperature. Mere descent into the crust of the earth will raise the temperature of the water until, if this descent be prolonged, a point far above 212° Fahr. may be reached. Experiments have shown that the chemical action of water is vastly increased by heat. Thus M. Daubrée exposed a glass tube containing about half

its weight of water to a temperature of about 400° C. At the end of a week he found the tube so entirely changed into a white, opaque, powdery mass as to present not the least resemblance to glass. The remaining water was highly charged with an alkaline silicate containing 63 per cent. of soda and 37 per cent. of silica, with traces of potash and lime. The white solid substance was ascertained to be composed almost entirely of crystalline materials. These consisted partly of minute perfectly limpid bipyramidal crystals of quartz, but chiefly of very small acicular prisms of wollastonite. It was found, moreover, that the portion of the tube which had not been directly in contact with the water was as much altered as the rest, whence it was inferred that at these high temperatures and pressures the vapour of water acts chemically like the water itself. (2.) In the second place, the effect of pressure must be recognized as most important in enabling water, especially when heated, to dissolve and retain in solution a larger quantity of mineral matter than it could otherwise do. In M. Daubrée's experiments just cited, the tubes were hermetically sealed and secured against fracture, so that the pressure of the greatly super-heated vapour had full effect. By this means, with alkaline water, he not only produced the two minerals above mentioned, but also feldspar and diopside.

It is important to observe that the three conditions required for these changes—the presence of alkaline water, a high temperature, and considerable pressure—are precisely those which it can be affirmed must exist abundantly within the crust of the earth. We must admit the possibility of rocks originally at the surface being depressed so as to come within the influence of internal heat, and to contain within their pores abundant interstitial water more or less charged with alkaline carbonates. Rocks under these conditions, so far as we can judge, can hardly escape internal decomposition and recomposition. Mere descent to a great depth beneath the surface will not necessarily result in metamorphism, as has been shown in the case of the Nova Scotian and of the South Welsh coal-field, where sandstones, shales, clays, and coal-seams can be proved to have been once depressed 14,000 to 17,000 feet below the sea-level, under an overlying mass of rock, and yet to have sustained no serious alteration. Perhaps the failure of change may be explicable on the supposition that these Carboniferous strata were comparatively dry. But where rocks possess sufficient interstitial water, and are depressed within the crust so as to be exposed to a considerable temperature and to great pressure, they must be metamorphosed,—the extent of the metamorphism depending partly upon the vigour of the attack made upon them by the water, partly on their own composition and proneness to chemical change, and partly upon the length of time during which the process is continued.

A metamorphosed rock must thus be one which has suffered a mineralogical rearrangement of its substance. It may or may not have been a crystalline rock originally. Any rock capable of alteration (and all rocks must be so in some degree) will, when subjected to the required conditions, become a metamorphic rock. The resulting structure, however, will, in most cases, bear witness to the original character of the mass. A sedimentary rock, for example, consisting of alternate layers of different texture and composition, will doubtless retain, even in its metamorphosed condition, traces of that fundamental structure. The water will travel more easily along certain layers than along others; some laminae will be more readily affected, or will give rise to a set of reactions different from those of contiguous layers. Hence the rearrangement and recrystallization due to metamorphism will take place along the predetermined lines of stratification, so long as these lines have not been effaced or rendered inoperative by any other geo-

logical structure. It is doubtless to this cause that the foliated character of gneiss, mica-schist, and so many other metamorphic rocks is to be ascribed.

In the process of metamorphism, therefore, as well as in that of fusion, to which reference has already been made, the influence of water would seem to have been always conspicuous. Indeed, as will be shown in part iv., it is extremely difficult in many cases to draw a line between the results of metamorphism and igneous fusion, or to decide whether a rock should be called igneous or metamorphic. It has been pointed out above, for example, that in many rocks which have undoubtedly been in a fluid condition, as proved by their injected veins and dykes, the constituent minerals have not appeared in the order of their respective fusibilities. Scheerer, Élie de Beaumont, and Daubrée have shown how the presence of a comparatively small quantity of water in such rocks has contributed to suspend their solidification, and to promote the crystallization of their silicates at temperatures considerably below the point of fusion. In this way the solidification of quartz in granite after the crystallization of the silicates, which would be unintelligible on the supposition of mere dry fusion, becomes explicable. The phenomena of metamorphism in the architecture of the earth's crust are discussed in part iv.

DIVISION II.—EPIGENE OR SURFACE ACTION.

It is on the surface of the globe and by the operation of agents working there that at present the chief amount of visible geological change is effected. In considering this branch of inquiry, we are not involved in the same preliminary difficulty regarding the very nature of the agencies as we found to be the case in the investigation of plutonic action. On the contrary, the surface agents are carrying on their work under our very eyes. We can watch it in all its stages, measure its progress, and mark in many ways how accurately it represents similar changes which for long ages previously must have been effected by the same means. But in the systematic treatment of this subject we encounter a difficulty of another kind. We discover that while the operations to be discussed are numerous and often complex, they are so interwoven into one great network that any separation of them under different subdivisions is sure to be more or less artificial, and to convey an erroneous impression. While, therefore, under the unavoidable necessity of making use of such a classification of subjects, we must bear always in mind that it is employed merely for convenience, and that in nature superficial geological action must be continually viewed as a whole, since the work of each agent has constant reference to that of the others, and is not properly intelligible unless that connexion be kept in view.

The movements of the air; the evaporation from land and sea; the fall of rain, hail, and snow; the flow of rivers and glaciers; the tides, currents, and waves of the ocean; the growth and decay of organized existence, alike on land and in the depths of the sea;—in short, the whole circle of movement, which is continually in progress upon the surface of our planet, are the subjects now to be examined. It would be desirable to adopt some general term to embrace the whole of this range of inquiry. For this end the word *epigene* may be suggested as a convenient term, and antithetical to *hypogene* or subterranean action.

The simplest arrangement of this part of Geological Dynamics will be into three sections:—

- I. AIR.—The influence of the atmosphere in destroying and forming rocks.
- II. WATER.—The geological functions of the circulation of water through the air and between sea and land, and the action of the sea.