§ 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 atmosphére. 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. The mere presence of pure water therefore within the pores in subteranean 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 re-crystallized 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 felspar 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 laminæ 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 pace along the predetermined lines of stratification, so long as these lines have not been effaced or rendered inoperative by any other geological 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.

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

III. Life.—The part taken by plants and animals in preserving, destroying, or reproducing geological formations.

The words destructive, reproductive, and conservative, employed in describing the operations of the epigene agents, do not necessarily imply that anything useful to man is destroyed, reproduced, or preserved. On the contrary, the destructive action of the atmosphere may turn barren rock into rich soil, while its reproductive effects sometimes turn rich land into barren desert. Again, the conservative influence of vegetation has sometimes for centuries retained as barren morass what might otherwise have become rich meadow or luxuriant woodland. The terms, therefore, are used in a strictly geological sense, to denote the removal and re-deposition of material, and its agency in preserving what lies beneath it.

Section I.—Air.

Its composition having been already treated of (*ante*, p. 220), we shall consider here (1) the motions, and (2) the geological action of the air, which arises partly from its composition, and partly from its movements.

I. Movements of the Air.

These are due to differences in the pressure or density of the atmosphere, the law being that the air always moves from where the pressure is high to where it is low. Atmospheric pressure is understood to be determined by two causes, temperature and aqueous vapour.

1. *Temperature.*—Warm air, being less dense than cold air, ascends, while the latter flows in to take its place. The unequal heating of the earth's surface, by causing upward currents from the warmed portions, produces horizontal currents from the surrounding cooler regions inwards to the central ascending mass of heated air. To this cause the trade winds and the familiar land and sea breezes are due.

2. *Aqueous Vapour.*—In proportion as the quantity of watery vapour increases, the density of the air lessens. Consequently moist air tends to rise as warmed air does, with a corresponding but often very violent inflow of the drier and consequently heavier air from the surrounding tracts. The ascent of the moist air lessens the atmospheric pressure, which is indicated by the fall of the barometer. When the up-streaming vapour rises into the higher regions of the atmosphere, it expands and cools, condensing into visible form, and descending in copious showers to the earth. Unequal and rapid heating of the air, or accumulation of aqueous vapour in the air, and possibly some other influences not yet properly understood, give rise to extreme disturbances of pressure, and consequently to storms and hurricanes. For instance, the barometer sometimes indicates in tropical storms a fall of an inch and a half in an hour, showing that somewhere about a twentieth part of the whole mass of the atmosphere has in that short space of time been displaced over a certain area of the earth's surface. No such sudden change can occur without resulting in the most destructive tempest or tornado. In Britain the tenth of an inch of barometric fall in an hour is regarded as a large amount, such as only accompanies great storms.[1] When the pressure of the air at one place is shown by the barometer to differ from that at a neighbouring locality at the same time, the wind will be observed to move on the whole from the area of high to the area of low pressure; and if the difference be great or sudden, the movement of the air may rise to the force of a hurricane until the equilibrium of pressure is restored.

The meteorological conditions of the atmosphere do not belong to the scope of this article (see Atmosphere, Climate, Meteorology). The reader, however, may note as of interest from a geological point of view the ascertained velocity and pressure exercised by the air in motion across the surface of the earth as expressed in the subjoined table :—

	Velocity in miles per hour.	Pressure in pounds per square foot.
Calm	0	0
Light breeze	14	1
Strong breeze	42	9
Strong gale	70	25
Hurricane	84	36

II. Geological Influences of the Air.

The paramount importance of the atmosphere as the vehicle for the circulation of temperature and moisture over the globe, and consequently as powerfully influencing the distribution of climate and the growth of plants and animals, must be fully recognized by the geologist. Attention will be confined at present to the direct changes produced on the surface of the earth by the air—(1) on land, and (2) on water.

1. *Its Influence on Land.*

I. Destructive Influences.—These are either (*a*) chemical or (*β*) mechanical, though in nature the two kinds of action are often inseparably interwoven.

(*a*) Under the denomination of *chemical* changes we include the oxidation of those minerals which can contain more oxygen, as in the peroxidation and precipitation of protosalts of iron; likewise the absorption of carbonic acid by rocks, and the production of alkaline and earthy carbonates and bicarbonates, which still further promote the process of decomposition. In the one case the active agent of change is the oxygen of the air, or rather of the aqueous vapour in the air, for perfectly dry air seems to have little or no oxidizing effect. A familiar illustration is afforded by the rust, or oxide, which forms on iron when exposed to moisture, though this iron may be kept long bright if allowed to remain screened from moist air. In the other case, the active agent is the carbonic acid of the air, though here again it appears to be requisite that moisture should intervene as the medium of introducing the acid to the substance which is to be altered by it. The occurrence of sulphuric and nitric acids in the air, especially noticeable in large towns, likewise leads to considerable corrosion of metallic surfaces, as well as of stones and lime. The mortar of walls may often be observed to be slowly swelling out and dropping off, owing to the conversion of the lime into sulphate. Great injury is likewise done from a similar cause to marble monuments in exposed graveyards.

As a rule, the changes effected by the air lead to many subsequent transformations. For example, the oxidation of the bisulphide of iron produces sulphuric acid, which decomposes silicates, carbonates, and other compounds with which it comes in contact. These changes, however, are more appropriately noticed under the head of rain (p. 267).

(*β*) Among the more recognizable *mechanical* changes of a destructive kind, brought about by the atmosphere, we may notice the following influences :—

1. *Expansion and Contraction.*—The effect of heat is to expand rocks, of cold to contract them. Strictly speaking, these results on the surface of the earth are due, not to the air, but to the heat-rays of the sun which reach the rocks through the air. In countries with a great annual range of temperature considerable difficulty is sometimes experienced in selecting building materials liable to be little affected by the alternate expansion and contraction which prevents the joints of masonry from remaining close and tight. In the United States, for example, with an annual thermometric range of more than 90° Fahr. this difficulty led to some experiments by Colonel Totten on the amount of expansion and contraction in different kinds of building-stones, caused by variations of temperature. It was found that in fine-grained granite the rate of expansion was ·000004825 for every degree Fahr. of increment of heat; in white crystalline marble it was ·000005668; and in red sandstone ·000009532, or about twice as much as in granite. If the daily variations in temperature are large, the effects are still more striking. In tropical climates with intensely hot days and extremely cold nights, the rapid nocturnal contraction produces sometimes a strain so great as to rival frost in its influence upon the surface of exposed rocks, disintegrating them into sand, or causing them to crack or peel off in skins or irregular pieces. Dr Livingstone found in Africa (12° S. lat., 34° E. long.) that surfaces of rock which during the day were heated up to 137° Fahr. cooled so rapidly by radiation at night that, unable to sustain the strain of contraction, they split and threw off sharp angular fragments from a few ounces to 100 or 200 ℔ in weight.[1]

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[1] Buchan's *Meteorology*, p. 266.

2. *Frost.*—Though properly belonging to the subject of the geological behaviour of water to be afterwards described in more detail, the disintegrating action of frost may be noticed here. In freezing water expands, and thereby exerts an enormous strain upon any enclosed cavities or walls which may confine it. The consequence of this action is that in countries exposed to frost a continual disintegration of the surface of rocks goes on. This superficial decay combines with the chemical and mechanical operations of the atmosphere to produce considerable modifications in the forms of rocks and cliffs.

3. *Wind.*—By driving loose sand over rocks, prevalent winds produce on them a scratched and polished surface, as has happened with ancient monuments buried in the sands of the African deserts.[2] It is said that at Cape Cod holes have even been drilled in window glass by the same agency.[3] Cavities are now and then hollowed out of rocks by the gyration in them of little fragments of stone or grains of sand kept in motion by the wind. Hurricanes form important geological agents upon land in uprooting trees, and thus sometimes impeding the drainage of a country, and giving rise to the formation of peat mosses.

Weathering of Rocks.—Under the term "weathering" are included all the superficial changes which rocks undergo in consequence of the action of atmospheric processes upon them. The nature and rapidity of the disintegration depend partly on the one hand upon the climate, and partly on the other upon the composition, texture, and exposure of the rocks. In very dry countries, where the range of temperature is not extreme, weathering is reduced to a minimum. But even if the climate be dry, considerable disintegration may be caused, as has been already explained, by rapid changes of temperature between day and night. It is where moisture prevails, however, that weathering chiefly takes place. The nature of the changes will be more properly considered in the section which is devoted to the action of rain.

II. Reproductive Influences.—These arise partly from the result of the chemical and mechanical disintegration involved in weathering, and partly from the transporting power of winds and aerial currents. Under the former head is the formation of soil; under the latter may be noticed the production of sand-hills, the fall of dust-showers and coloured rain, and the transport of seeds.

Soil.—Of the detritus produced by the action of the air on rocks, and washed away by rains and streams, part remains on the land and forms soil. All soil may be considered as the result of the decomposition of rocks, mingled with decayed vegetable and animal matter. Were it not for the action of rain in washing the loose materials to a greater or less distance from their source, the soil of every locality ought to be merely the decayed upper surface of the rocks underneath. But wherever rain falls, the soil is moved from higher to lower levels. Hence in some cases a good soil is laid down upon rocks which of themselves would only produce a poor one. This action of rain in the formation of soil is further alluded to on p. 270, and the co-operative influence of plant and animal life on p. 289.

Sand-hills or Dunes.—Winds blowing continuously upon loose materials, such as sand, drive them onward, and pile them into irregular heaps and ridges, called "dunes." This takes place more especially on windward coasts either of the sea or of large inland lakes, where the shores are sandy; but similar effects may be seen even in the heart of a continent, as in the sandy deserts of the Sahara and of Arabia. The dunes travel inland in parallel, irregular, and often confluent ridges, between which rain-water is sometimes arrested to form pools (*étangs* of the French coasts), where formations of peat occasionally take place. On the coast of Gascony the sea for 100 miles is so barred by sand-dunes that in all that distance only two outlets exist for the discharge of the drainage of the interior. As fast as one ridge is driven away from a beach another forms in its place, so that a series of huge sandy billows, as it were, is continually on the move from the sea margin towards the interior. A stream or river may temporarily arrest their progress, but eventually they push the obstacle aside or in front of them. In this way the river Adour, on the west coast of France, has had its mouth shifted two or three miles. Occasionally, as at the mouths of estuaries, the sand is blown across so as gradually to exclude the sea, and thus to aid the fluviatile deposits in adding to the breadth of the land.[4] The coast of Norfolk is fringed with sand-hills 50 to 60 feet high. On parts of the coast of Cornwall, the sand consists mainly of fragments of shells and corallines, and through the action of rain becomes sometimes indurated into a compact stone by carbonate of lime or oxide of iron. Long tracts of blown sand are likewise found along many parts of the Scottish and Irish coast-lines.

On the western border of the European continent extensive sand-dunes exist. They extend for many leagues along the French coast, and thence, by Flanders and Holland, round to the shores of Courland and Pomerania. In Denmark they are said to cover an area of 260 square miles. On the coast of Holland they are sometimes, though rarely, 260 feet high,—a common average height being 50 to 60 feet. The breadth of this maritime belt of sand varies considerably. On the east coast of Scotland it ranges from a few yards to 3 miles; on the opposite side of the North Sea it attains on the Dutch coast sometimes to as much as 5 miles. The rate of progress of the dunes towards the interior depends upon the wind, the direction of the coast, and the nature of the ground over which they have to move. On the low and exposed shores of the Bay of Biscay, when not fixed by vegetation, they travel inland at a rate of about 16½ feet; in Denmark at from 3 to 24 feet per annum. In the course of their march they envelop

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[1] Livingstone's *Zambesi*, pp. 492, 516.

[2] For an account of this action of drifting sand in North America see Blake in *Pacific Railroad Report*, v. 92, 230.

[3] Dana's *Manual*, p. 631.

[4] For accounts of sand-dunes, their extent, progress, structure, and the means employed to arrest their progress, the reader may consult Andersen's *Klitformationent*, 1 vol. 8vo, Copenhagen, 1861; Laval in *Annales des Ponts et Chaussées*, 1847, 2me sem.; and Marsh's *Man and Nature*, 1864, and the works cited by him. See also Élie de Beaumont, *Leçons de Géologie*, vol. i.

houses and fields; even whole parishes and districts once populous have been overwhelmed by them.[1]

Along the margins of large lakes and inland seas many of the phenomena of an exposed sea-coast are repeated, and on no inferior scale. Among these must be included sand-dunes, such as occur at the south-eastern end of Lake Michigan and on the eastern borders of the Caspian Sea. The shifting of vast waves of sand by the wind is exemplified on the grandest scale in the sandy deserts of Africa, Arabia, and Central Asia. Such arid wastes of loose sand, situated far inland and far distant from any sheet of fresh water, suggest curious problems in physical geography. Their sites may have been at a comparatively recent geological period covered by the sea; or, lying in rainless climates and having their surfaces exposed to the disintegrating effects of great extremes of temperature, the tracts may have become sandy and barren through atmospheric disintegration. The desert of the Sahara furnishes a good illustration of a dried-up sea-bed. In the rainless tract to the east of the Red Sea lie the great sandy deserts and hills of Arabia, of which Mr Palgrave has given so graphic a narrative. Captain Sturt found vast deserts of sand in the interior of Australia, with long lines of dunes 200 feet high, united at the base and stretching in straight lines as far as the eye could reach. In the south-east of Europe great tracts of sandy desert occur in Poland, and run through the southern provinces of Russia.

Dust-showers, Blood-rain.—In tropical countries, where great droughts are succeeded by violent hurricanes, the dust or sand of dried lakes or river-beds is sometimes borne away into the upper regions of the atmosphere, where, meeting with strong aerial currents which transport it for hundreds and even thousands of miles, it may descend again to the surface, in the form of "red-fog," "sea-dust," or "sirocco-dust." This transported material, usually of a brick-dust or cinnamon colour, is occasionally so abundant as to darken the air and obscure the sun, and to cover the decks, sails, and rigging of vessels which may even be hundreds of miles from land. Rain falling through such a dust-cloud mixes with it, and descends either on sea or land as what is popularly called "blood-rain." This is frequent on the north-west of Africa, about the Cape Verd Islands, in the Mediterranean, and over the bordering countries. A microscopic examination of this dust by Ehrenberg led him to the belief that it contains numerous diatoms of South American species; and he inferred that a dust-cloud must be swimming in the atmosphere, carried forward by continuous currents of air in the region of the trade-winds and anti-trades, but suffering partial and periodical deviations. But much of the dust must come from the sandy plains and desiccated pools of the north of Africa. Daubrée recognized in 1865 some of the Sahara sand which fell in the Canary Islands. On the coast of Italy a film of sandy clay, identical with that in parts of the Libyan desert, is occasionally found on windows after rain. In the middle of last century an area of northern Italy, estimated at about 200 square leagues, was covered with a layer of dust which in some places reached a depth of one inch. Should the travelling dust encounter a cooler temperature, it may be brought to the ground by snow, as has happened in the north of Italy, and more notably in the east and south-east of Russia, where the snows are sometimes rendered dirty by the dust raised by the winds on the Caspian steppes. It is easy to see that a prolonged continuance of this action must give rise to widespread deposits of dust, mingled with the soil of the land, and with the silt and sand of lakes, rivers, and the sea; and that the minuter organisms of tropical regions may thus come to be preserved in the same formations with the terrestrial or marine organisms of temperate latitudes.[2]

Transportation of Seeds.—Besides the transport of dust and minute organisms for distances of many thousands of miles, the same agency may come into play also in the transport of living seeds, which, finally reaching a congenial climate and soil, may take root and spread. We are yet, however, very ignorant as to what extent this cause has actually operated in the establishment of any given local flora. With regard to the minute forms of vegetable life, indeed, there can be no doubt as to the efficacy of the wind to transport them across vast distances on the surface of the globe. Upwards of 300 species of diatoms have been found in the deposits left by dust-showers. Among the millions of organisms thus transported it is hardly conceivable that some should not fall into a fitting locality for their continued existence and the perpetuation of their species.

2. *Influence of the Air on Water.*

The action of the air upon water will be more fitly noticed in the section devoted to water (p. 285). It will be enough to notice here—

1. *Ocean Currents.*—The in-streaming of air from cooler latitudes towards the equator causes a drift of the sea-water in the same direction. Owing to the rotation of the earth, these aerial currents tend to take a more and more westerly trend as they approach the equator. This they communicate to the marine currents, which, likewise moving into regions having a greater velocity of rotation than their own, are all the more impelled in the same westerly direction. Hence the westerly belt or equatorial current, which flows across the great ocean. Owing to the position of the continents across its path, this great current cannot move uninterruptedly round the earth. It is split into branches which turn to right and left, and, bathing the shores of the land, carry some of the warmth of the tropics into more temperate latitudes.

2. *Waves.*—The impulse of the wind upon a surface of water throws that surface into pulsations which range in size from mere ripples to huge billows. Long-continued gales from the seaward upon an exposed coast indirectly effect much destruction, by the formidable battery of billows which they bring to bear upon the land. Wave-action is likewise seen in a marked manner when wind blows strongly across a broad inland sheet of water, such as Lake Superior. (See p. 279.)

3. *Alteration of the Water-level.*—When the wind blows freshly for a time down a lake or into a bay or arm of the sea, it drives the water before it, and keeps it temporarily at a higher level, at the further or windward side. In a tidal sea, such as that which surrounds Great Britain, and which sends abundant long arms into the land, this action can often be studied. It is no infrequent occurrence that a high tide and a gale should happen at the same time. Whenever that takes place, then at those bays or firths which look windward the high tide rises to a greater height than elsewhere. With this conjunction of wind and tide, considerable damage to property has sometimes been done by the flooding of warehouses and stores, while even a sensible destruction of cliffs and sweeping away of loose materials may be chronicled by the geologist. On the other hand, a wind from the opposite quarter will drive the water out of the inlet, and thus make the water-level lower than it should otherwise be.

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[1] This destruction has been, during the last quarter of a century, averted to a great extent by the planting of pine forests, the turpentine of which has become the source of a large revenue.

[2] See Humboldt on dust whirlwinds of the Orinoco, *Aspects of Nature*; also Maury, *Phys. Geog. of Sea*, chap. vi.; and Ehrenberg's *Passat-Staub und Blut-Regen*, 1847.

Section II.—Water.

Of all the terrestrial agents by which the surface of the earth is geologically modified, by far the most important is water. When following hypogene changes in a foregoing part of this article, we found how large a share is taken by water in the phenomena of volcanoes and other subterranean movements. When we returned to the surface of the earth and began to watch the operations of the atmosphere, we saw how impossible it is to consider these apart from the action of the aqueous vapour by which the atmosphere is pervaded. We must now study in detail the working of this wonderful geological agent itself.

The substance which we term water exists on the earth in three well-known forms—(1) gaseous, as invisible vapour; (2) liquid, as water; and (3) solid, as ice. The gaseous form has already been noticed in our inquiry into the geological characteristics of the air. It is in the air that this condition of the water-substance prevails. By the sun's heat vast quantities of vapour are continually raised from the surface of the seas, rivers, lakes, snow-fields, and glaciers of the world. This vapour remains invisible until the air containing it is cooled down to below its dew-point, or point of saturation,—a result which follows upon the union or collision of two aerial currents of different temperatures, or the rise of the air into the upper cold regions of the atmosphere, where it is chilled by expansion, by radiation, and by contact with cold mountains. At first minute particles appear, which either remain in the liquid condition, or, if the temperature is sufficiently low, are at once frozen into ice. As these changes take place over considerable spaces of the sky, they give rise to the phenomena of clouds. Further condensation augments the size of the cloud-particles, and at last they fall to the surface of the earth, if still liquid, as rain; if solid, as snow or hail; and if partly solid and partly liquid, as sleet. As the vapour is largely raised from the ocean surface, so in great measure it falls back again directly into the ocean. A considerable proportion, however, descends upon the land, and it is this part of the condensed vapour which we have now to follow. Upon the higher elevations it falls as snow, and gathers there into snow-fields, which, by means of glaciers, send their drainage down towards the valleys and plains. Elsewhere it falls chiefly as rain, some of which sinks underground to gush forth again in springs, while the rest pours down the slopes of the land, feeding brooks and torrents, which, swollen further by the springs, gather into broader and yet broader rivers, whereby the drainage of the land is carried out to sea. Thence once more the vapour rises to reappear in clouds, and feed the innumerable water-channels by which the land is furrowed from mountain-top to sea-shore.

Here then is a vast system of circulation, ceaselessly renewed. And in that system there is not a drop of water which is not busy with its allotted task of changing the face of the earth. When the vapour ascends into the air it is almost chemically pure. But when, after being condensed into visible form, and working its way over or under the surface of the land, it once more enters the sea, it is no longer pure, but more or less loaded with material taken by it out of the air, rocks, or soils through which it has travelled. Day by day the process is advancing. So far as we can tell, it has never ceased since the first shower of rain fell upon the earth. We may well believe, therefore, that it must have worked marvels upon the surface of our planet in past time, and that it may effect vast transformations in the future. As a foundation for such a belief let us now inquire what it can be proved to be doing at the present time.

The subject of the geological operation of water upon the globe may be conveniently studied under the following subdivisions:—

A. Terrestrial Waters.—Under this head are to be considered—(1) the liquid state, including rain, underground water, brooks, rivers, and lakes; and (2) the solid state—frost, river-ice, snow, hail, glaciers.

B. Oceanic Waters.—Including the influence of marine currents, tides, and waves, and the part taken by the sea in the general geological *régime* of the earth.

A. TERRESTRIAL WATERS.

I. IN THE LIQUID STATE.

§ 1. *Rain.*

Rain effects two kinds of changes upon the surface of the land. (1.) It acts *chemically* upon soils and stones, and sinking under ground continues, as we shall find, a great series of similar reactions there. (2.) It acts *mechanically*, by washing away loose materials, and thus powerfully affecting the contours of the land.

I. Chemical Action.—This depends mainly upon the nature and proportion of the substances abstracted by rain from the air in its descent to the earth. Rain always absorbs a little air, and as we have already seen (p. 220) air always contains carbonic acid as well as other ingredients, in addition to its nitrogen and oxygen. If rain be regarded as an agent washing the air and taking impurities out of it, we may the better realize how by means of these it is enabled to work many chemical changes which, were it to reach the earth as pure water, it could not accomplish.

Composition of Rain-Water.—Numerous analyses of rain-water show that it contains in solution about 25 cubic centimetres of gases per litre. An average proportional percentage is by measure—nitrogen, 66·4; oxygen, 31·2; carbonic acid, 2·4,—the oxygen being in greater proportion than in air, owing to its greater solubility in water. Common salt, ammonia, sulphates, nitric acid, inorganic dust, and organic matter are usually present in minute quantities in rain water. So far as we know at present, the three ingredients which are chiefly effective in the chemical reactions due to rain are the oxygen, carbonic acid, and organic matter.[1]

Permeability of all Rocks by Water.—Though minerals and rocks differ vastly in their degree of porousness, there is none known which is not in some degree permeable by water. Even such hard and apparently impenetrable substances as flint and agate are found to be permeable. For, in fact, rocks and minerals when examined with the microscope are seen to be made up of variously-shaped grains, crystals, or particles, and it is in the minute channels and interstices between these particles, or even through the particles themselves, that the water works its way. Evidently, the smaller the interstices the less easily will the water force a passage into or through the stone. This permeability, though well marked upon the surface of the land, becomes still more so underground, where the rocks are sometimes quite saturated with water.

Liability of all Rocks to alteration by Water.—There is probably no known substance which is not, under some condition, soluble in water containing carbonic acid or other natural reagent. Rain-water, descending with the gases, acids, and organic matter it has abstracted from the air and soil, effects a chemical disintegration of the rocks. This action was referred to in the description of the air as

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[1] The organic matter is revealed by the putrid smell which long-kept rain water gives out. The reader who wishes to pursue this subject may consult the elaborate tables of analyses in Dr Angus Smith's *Air and Rain*. See also the section on air, *ante*, p. 220.

partly due to atmospheric moisture, but it is chiefly carried on by rain. And as rain is so widely and almost universally distributed over the globe, this chemical action must be of very general occurrence.

Nature of the Changes effected.—Confining our attention to its three chiefly active ingredients, we find that rain water reacts chemically upon rocks by—1. *Oxidation.*—The prominence of oxygen in rain-water, and its readiness to unite with any substance which can contain more of it, render this a marked feature of the passage of rain over rocks. A thin oxidized pellicle is formed on the surface, and this, if not at once washed off by the rain, sinks deeper until a crust is formed over the stone. As already remarked, this process is simply a rusting of those minerals which, like metallic iron, have no oxygen, or have not their full complement of it. 2. *Deoxidation.*—Organic matter having an affinity for more oxygen decomposes peroxides by depriving them of some part of their share of that element, and reducing them to protoxides. These changes are especially noticeable among the iron oxides so abundantly diffused among rocks. Hence rain-water, in sinking through soil and obtaining such organic matter, becomes thereby a reducing agent. 3. *Solution.*—This may take place either by the simple action of the water, as in the solution of rock-salt, or by the influence of the carbonic acid present in the rain. Of the latter (*Carbonation*) a familiar example is the corrosion of marble slabs down which rain has trickled for a time. The carbonic acid dissolves some of the lime, which as a bicarbonate is held in solution in the carbonated water, but is deposited again when the water loses its carbonic acid or evaporates. It is not merely carbonates, however, which are liable to this kind of destruction. Even silicates of lime, potash, and soda, combinations existing abundantly as constituents of rocks, are attacked; their silica is liberated, and their alkalies or alkaline earths, becoming carbonates, are removed in solution. 4. *Hydration.*—Some minerals, containing little or no water, and therefore called anhydrous, when exposed to the action of the atmosphere, absorb water, or become hydrous, and are then usually more prone to further change. Hence the rocks of which they form part become disintegrated.

Weathering.—The weathering of rocks is dependent upon two sets of conditions—(1) meteorological, as the range of temperature, abundance of moisture, height above the sea, and exposure, and (2) lithological,—the composition and texture of the rocks themselves. As regards the composition of rocks, those which consist of particles liable to little chemical change from the influence of moisture are best fitted to resist weathering, provided their particles have sufficient cohesion to withstand the mechanical processes of disintegration. Siliceous sandstones are excellent examples of this permanence. Consisting wholly or mainly of the durable mineral quartz, they are sometimes able so to withstand decay that buildings made of them still retain, after the lapse of centuries, the chisel-marks of the builders. Some rocks which yield with comparative rapidity to the chemical attacks of moisture show no marks of disintegration on their surface, which remains clean and fresh. This is particularly the case with limestones. The reason lies obviously in the fact that limestone when pure is wholly soluble in acidulous water. Rain falling on this rock removes some of it in solution, and will continue to do so until the rock is dissolved away. It is only where the limestone contains impurities that a weathered crust of more or less insoluble particles remains behind. Hence the relative purity of limestones may be roughly determined by comparing their weathered surfaces, where, if they contain much sand, the grains will be seen projecting from the calcareous matrix, and where should the rock be very ferruginous, the yellow hydrous peroxide or ochre will be found as a powdery crust. In limestones containing abundant encrinites, shells, or other organic remains, the weathered surface commonly presents the fossils standing out in relief. This seems to arise from the crystalline arrangement of the lime in the organic structures, whereby they are enabled to resist disintegration better than the general mechanically aggregated matrix of the rock. An experienced fossil collector will always search well those weathered surfaces, for he often finds there, delicately picked out by the weather, minute and frail fossils which are wholly invisible on a freshly broken surface of the stone. Many rocks weather with a thick crust or even decay inwards for many feet or yards. Basalt, for example, often shows a yellowish-brown ferruginous layer on its surface, formed by the conversion of its felspar into kaolin and the removal of its silicate of lime as carbonate, by the hydration of its olivine and augite and their conversion into serpentine, saponite, or some other hydrous magnesian silicate, and by the conversion of its magnetite into limonite. Granite sometimes shows in a most remarkable way the distance to which weathering can reach. It may often be dug into for a depth of 20 or 30 feet, the quartz crystals and veins retaining their original positions, while the felspar is completely kaolinized.

It is to the effects of weathering that the abundant fantastic shapes assumed by crags and other rocky masses are due. Most varieties of rock have their own characteristic modes of weathering, whereby they may be recognized even from a distance. To some of these features reference will be made in a subsequent section.

II. Mechanical Action.—When a rock has been so corroded by weathering that the cohesion of the particles on its exposed surface is destroyed, these particles are washed off by rain. This detritus is either held in suspension in the little runnels into which the rain-drops gather as they begin to flow over the land, or is pushed by them along the surface. In this way the rain carries off by mechanical movement what it has already loosened by chemical action.

III. Results of Rain-Action.—It is evident that the general result of the fall of rain upon a land-surface must be a disintegration and consequent lowering of that surface. At first we may be inclined to imagine that this waste must be so slow and slight as to be hardly appreciable. But a little observation will suffice to furnish many proofs of its existence and comparatively rapid progress in some places. We are familiar, for example, with the pitted channelled surface of the ground lying immediately under the drip of the eaves of a house. We know that the fragments of stone and gravel are left sticking up prominently because the earth around and above them has been washed away, and because, being hard, they resist the action of the falling drops and screen the earth below them. On a far larger scale we may notice the same kind of operation in districts of conglomerate, where the larger blocks, serving as a protection to the rock underneath, come to form as it were the capitals of slowly-deepening columns of rock. In the same way in certain valleys of the Alps a stony clay is cut by the rain into pillars, each of which is protected by, and indeed owes its existence to, a large block of stone which lay originally in the heart of the mass. These columns are of all heights, according to the positions in which the stones may have originally lain. There are instances, however, where the disintegration has been so complete that only a few scattered fragments remain of a once extensive stratum, and where it may not be easy to realize that these fragments are not transported boulders. In Dorsetshire and Wiltshire, for example, the surface of the country is in some parts so thickly strewn with fragments of sandstone and conglomerate "that a person may almost leap from one stone to another without touching the ground. The stones are frequently of considerable size, many being four or five yards across, and about four feet thick."[1] They have been used for the huge blocks of which Stonehenge and other of the so-called druidical circles have been constructed, hence they have been termed Druid Stones. Other names are Sarsen Stones (supposed to indicate that their accumulation has been popularly ascribed to the Saracens), and Grey Wethers, from their resemblance in the distance to flocks of (wether) sheep. They are found lying abundantly on the chalk, suggestive at first of some former agent of transport by which they were brought from a distance. It is now, however, generally admitted that they are simply fragments of some of the sandy Tertiary strata which once covered the districts where they occur, and that while the softer portions of these strata have been carried away, the harder parts (their hardness perhaps increasing by exposure) have remained behind as Grey Wethers, and have subsequently suffered from the inevitable splitting and crumbling action of the weather.

But it is not from any single example, however striking, that the real importance of rain as a geological agent can be adequately realized. To form a true conception of this momentous action, we need to watch what takes place over a wide region. The whole land-surface over which rain falls is exposed to waste. As Hutton long ago insisted, the superficial covering of decayed rock or soil is constantly, though slowly, travelling outward and downward to the sea. In this ceaseless transport rain acts as the great carrying agent. The particles of rock loosened by atmospheric waste, by frost or the chemical disintegration of the rain itself, are washed off to form new soil. But they as well as the particles of the soil are step by step moved downward over the face of the land till they reach the nearest brook or river, whence their seaward progress may be rapid. A heavy rain discolours the water-courses of a country, because it loads them with the fine debris which it removes from the general surface of the land. In this way rain serves as the means whereby the work of the other disintegrating forces is made conducive to the general degradation of the land. The decomposed crust produced by weathering, which would otherwise accumulate over the solid rock and protect it from further decay, is removed by rain so as to expose a fresh surface to further decomposition. This decay is general and constant, but not uniform. In some places, from the nature of the rock, from the flatness of the ground, or from other causes, rain works under great difficulties. There the rate of waste must consequently be extremely slow. In other places, again, the rate may be rapid enough to be readily appreciable from year to year. A survey of this department of geological activity shows how the unequal wasting by rain has helped to produce the details of the present relief of the land, those tracts where the destruction has been greatest forming hollows and valleys, others, where it has been less, rising into ridges and hills.

Rain-action is not always merely destructive. Usually it is accompanied by reproductive effects, and, as already remarked, the mouldered rock which it washes off furnishes materials for the formation of soil. In favourable situations it has gathered together accumulations of loam and earth from neighbouring higher ground—the "brick-earth," "head," and "rain-wash" of the south of England—earthy deposits, sometimes full of angular stones, derived from the subaerial waste of the rocks of the neighbourhood.[2]

§ 2. *Underground Water.*

When rain falls upon the land its further progress becomes twofold. The greater part of it sinks into the ground and apparently disappears; the rest flows off into runnels, brooks, and rivers, and in this way moves downward to the sea. It is most convenient to follow first the course of the subterranean water.

We have seen that all rocks are more or less porous. They are moreover traversed by abundant joints and cracks. Hence, from the bed of the ocean, from the bottoms of lakes and rivers, as well as from the surface of the land on which rain falls, water is continually filtering downward into the rocks beneath. To what depth this descent of the surface water may go is not known. It may reach as far as the intensely heated interior of the planet, for, as the researches of M. Daubrée have shown, capillary water has the capacity of penetrating rocks even against a high counter-pressure of vapour. The water at extreme depths may be under such pressure as to retain its liquid condition at a red or even at a white heat. Probably the depth to which the water descends varies indefinitely according to the varying nature of the rocky crust. Some shallow mines are practically quite dry, while others of great depth require large pumping engines to keep them from being flooded by the water which pours into them from the surrounding rocks. As a rule, however, the upper layers of rock are fuller of moisture than those deeper down.

The water which in this way sinks into the earth is not permanently removed from the surface, though there may perhaps be a slight loss due to absorption and chemical alteration of the rocks. It accumulates underneath, until by the pressure of the descending column it is forced to find a passage through joints or fissures upward to the surface. The points at which it issues are termed *springs*. In most districts the rocks underneath are permeated with water below a certain limit which is termed the *water-level*. This line is not a strictly horizontal one like that of the surface of a lake. Moreover, it is liable to rise and fall according as the seasons are wet or dry. In some places it lies quite near, in others far below, the surface. A well is an artificial hole dug down below the water-level, into which the water percolates. Hence, when the water-level happens to be at a small depth the wells are shallow, when at a great depth they require to be deep.

Since the rocks underneath the surface vary greatly in porosity, some contain far more water than others. It often happens that, percolating along some porous bed, the subterranean water finds its way downward until it passes under some more impervious[3] rock. Hindered in its progress, it accumulates in the porous bed, from which it may be able to find its way up to the surface again only by a tedious circuitous passage. If, however, a bore-hole be sunk through the upper impervious bed down to the water-charged stratum below, the water will eagerly avail itself of this artificial channel of escape, and will rise in the hole, or even rush up and gush out as a *jet d'eau* above ground. Wells of this kind are now largely employed. They bear the name of *Artesian*, from the old province of Artois in France, where they have long been in use.

That the water really circulates underground. and passes

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[1] See *Descriptive Catalogue of Rock Specimens in Jermyn Street Museum*, 3d ed.; Prestwich, *Quart. Journ. Geol. Soc.*, x. p. 123; Whitaker, *Geological Survey Memoir on parts of Middlesex*, &c., p. 71.

[2] See Austen, *Quart. Journ. Geol. Soc.*, vi. 94, vii. 121; Foster and Topley, *Quart. Journ. Geol. Soc.*, xxi. 446.

[3] This term *impervious* must evidently be used in a relative and not in an absolute sense. A stiff clay is practically impervious to the trickle of underground water; hence its employment as a material for puddling (that is, making water-tight) canals and reservoirs. But it contains abundant interstitial water, on which indeed its characteristic plasticity depends.