although coöperating, as a rule, with water, pressure, and chemical action.

Local metamorphism or alteration of sedimentary rocks is observed chiefly in the neighborhood of masses of igneous rocks; and in nearly all such instances the volcanic heat is plainly the principal agent. Thus, the native coke (**81**) has been formed, as coke usually is, by the action of heat upon bituminous coal; the heat coming in this instance from a dike of trap which has broken through a coal-bed. The alteration is most marked next to the dike, and dies out at a distance of a few feet or yards. Under very similar conditions chalk has been changed locally to the hard, dense limestone or marble shown in the next specimen (**82**). The specimen of black slate from the vicinity of large dikes of diabase at East Point, Nahant (**83**), has been very thoroughly baked and indurated by the heat of the dikes; and the expansion of vapors due to the heat has developed lenticular cavities along certain planes in the rock, in which epidote and other minerals resulting from the metamorphism have crystallized. A still more perfect example of crystallization is seen in the slate from the quarries in Somerville (**84**). The pyrite crystals are there observed in the slate only within a few inches or feet of the trap dikes. The next specimen (**85**) is slate from near the contact with the granite in Quincy. A crystalline micaceous mineral has been largely developed in it, apparently at the time when it was pervaded by the heat of the molten granite. Metamorphism is not limited to the sedimentary rocks; but the eruptive rocks are also subject to extensive morphologic and chemical changes; and

through the combined action of mechanical and chemical forces they frequently come to resemble very closely some of the crystalline schists and gneisses (**86**), and other sedimentary rocks.

SUPERFICIAL OR AQUEOUS AGENCIES.

When we think of the ocean with its waves, tides, and currents, of the winds, and of the rain and snow, and the vast net-work of rivers to which they give rise, we realize that the energy or force manifested upon the earth's surface resides chiefly in the air and water — in the earth's fluid envelop and not in its solid crust. And it is an easy matter to show that, with the exception of the tidal waves and currents, which of course are due chiefly to the attraction of the moon, nearly all this energy is merely the transformed heat of the sun. Now the air and water are two great geological agencies, and therefore the geological effects which they produce are traceable back to the sun. Organic matter is another important geological agent; but all are familiar with the generalization that connects the energy exhibited by every form of life with the sun.

Of this trio of geological agencies operating upon the earth's surface and vitalized by the sun — *water*, *air*, and *organic matter* — the water is by far the most important, and so it is common to call these collectively the aqueous agencies. The aqueous agencies include, on one side, *air* and *water*, or *inorganic* agencies; and, on the other, *animals* and *plants*, or *organic* agencies.

The collection is arranged to illustrate, as well as may be, the operation of these two classes of agencies, beginning with the air and water. But it is necessary, first, to note that nearly all the geological work of the superficial or aqueous agencies may be considered under the two general heads of erosion, or the wearing away of the rocks of the land, and deposition, or the formation in the sea from the material worn off from the land of the various kinds of sedimentary rocks; and that each of these processes may be chiefly chemical or chiefly mechanical in its nature.

AIR AND WATER, OR INORGANIC AGENCIES.

CHEMICAL EROSION.

The illustration begins with a local example (**41–44**). The first specimen (**41**) is a sound, fresh piece of the rather common rock, diabase; and those who are acquainted with minerals will recognize that the light-colored grains in the rock are feldspar, and the dark, augite. This specimen came from a depth in the quarry, and has not been exposed to the action of the weather.

The second specimen (**42**) differs from the first, apparently, as much as possible; and yet, except in being somewhat finer grained, it was originally of precisely similar composition and appearance. In fact, it is a portion of the same rock, but a *weathered* portion. In this we can no longer recognize the feldspar and augite as such, but both these minerals are very much changed, while in the place of a strong, hard rock we have an incoherent, friable mass, which is, externally at least, easily

crushed to powder; and with the next step in the weathering, as we may readily observe in the natural ledges, the rock is completely disintegrated, forming a loose earth or soil.

The third and fourth specimens (**43–44**) are two examples of such natural powders; and by washing these (especially the finer one) with water, we can prove that they consist of an impalpable substance which we may call clay, and angular grains which we may call sand. The sand-grains are really portions of the feldspar not yet entirely changed to clay.

Thus we learn that the result of the exposures of this hard rock to the weather is that it is reduced to the condition of sand and clay. What we mean especially by the weather are *moisture* and certain constituents of the air, particularly *carbon dioxide*. The action of the weather on the rocks is mainly chemical. With a very few exceptions, the principal minerals of which rocks are composed, such as feldspar, hornblende, augite, and mica, are silicates, *i. e.*, consist of silicic acid or silica combined with various bases, especially aluminum, magnesium, iron, calcium, potassium, and sodium.

Now the silica does not hold all these bases with equal strength; but carbon dioxide, in the presence of moisture, is able to take the sodium, potassium, calcium, and magnesium away from the silica in the form of carbonates, which, being soluble, are carried away by the rain-water. The silicate of aluminum, with more or less iron, takes on water at the same time, and remains behind as a soft, impalpable powder, which is kaolin or common clay.

In the case of the diabase, continued exposure to the weather would reduce the whole mass to clay. But other rocks contain grains of quartz, a hard mineral

which cannot be decomposed, and it always forms sand. Certain classes of rocks, too, such as the limestones and some iron-ores, are completely dissolved by water holding carbon dioxide in solution, and nothing is left to form soil, except usually a small proportion of insoluble impurities like sand or clay. Thus, the soil on the upper side of the specimen of limestone (**45**) is the insoluble impurity or clay contained in a considerable thickness of the limestone which has been removed by solution.

It is interesting to notice how these agents of decay get at the rocks. Neither water nor air can penetrate the solid rock or mineral to any considerable extent, so that practically the action is limited to surfaces, and whatever multiplies surfaces must favor decomposition.

First, we have the upper surface of the rock where it is bare, but more especially where it is covered with soil, for there it is always wet. All rocks are naturally divided by joints into blocks which are frequently more or less regular, and often of quite small size. Water and air penetrate into these cracks and decompose the surfaces of the blocks, and thus the field of their operations is enormously extended. These rock-blocks sometimes show very beautifully the progress of the decomposing agents from the outside inward by concentric layers or shells of rotten material, which, in the larger blocks, often envelop a nucleus of the unaltered rock (**46**).

It is interesting to observe, too, that these concentric lines of decay cut off the angles of the original blocks, so that the undecomposed nucleus, when it is found, is approximately spherical instead of angular.

In the rocks also we find many imperfect joints and minute cracks. In cold countries these are extended and widened by the expansive power of freezing water, and thus the surfaces of decomposition become constantly greater.

Nearly all rocks suffer this chemical decomposition when exposed to the weather, but in some the decay goes on much faster than in others. Diabase is one of the rocks which decay most readily; while granite (**48**) is, among common rocks, one of those that resist decay most effectually.

The specimen from Louisburg Square (**47**) shows, however, how rapidly even the granites may yield under favorable conditions, when frost coöperates with the chemical agents.

The caverns which are so large and numerous in most limestone countries are splendid examples of the solvent action of meteoric waters, being formed entirely by the dissolving out of the limestone by the water circulating through the joint cracks. The process must go on with extreme slowness at first, when the joints are narrow, and more rapidly as they are widened and more water is admitted. We get some idea, too, of the magnitude of the results accomplished by these silent and unobtrusive agencies when we reflect that almost all the loose earth and soil covering the solid rocks are simply the insoluble residue which carbon dioxide and water cannot remove.

In low latitudes, where a warm climate accelerates the decay of the rocks, the soil is usually from 50 to 300 feet deep.

The remaining specimens on the third shelf (**49–52**) are a very perfect illustration, from the vicinity of Washington, of the characteristic sedentary or residuary soil of the South, showing four stages in the transformation of a hard, gray, micaceous gneiss into a bright red clay soil, and matching the diabase series (**41–44**) from this vicinity.

MECHANICAL EROSION—ON THE EDGE OF THE LAND.

Whoever has been on the shore must have noticed that the sand along the water's edge is kept in constant motion by the ebb and flow of the surf. Where the beach is composed of gravel or shingle the motion is evident to the ear as well as the eye; and when the surf is strong, the rattling and grinding of the pebbles as they are rolled up and down the beach develops into a roar.

The constant shifting of the grains of sand, pebbles, and stones is, of course, attended by innumerable collisions, which are the cause of the noise. Now it is practically impossible, as one may easily prove by experiment, to knock or rub two pieces of stone together, at least so as to produce much noise, without abrading their surfaces; small particles are detached, and sand and dust are formed.

That this abrasion actually occurs in the case of the moving sand is most beautifully shown by the sand-blast. We are to conclude, then, that every time a pebble, large or small, is rolled up and down the beach it becomes smaller, and some sand and dust or clay are formed which are carried off by the water.

But what are the pebbles originally? This question is not difficult. A little observation on the beach shows that the pebbles are not all equally round and smooth, but many are more or less angular; and we soon see that it is possible to select a series showing all gradations between the most perfectly rounded forms and angular

fragments of rock that are only slightly abraded on the corners. The three principal members of such a series are shown in the specimens from the beach on Marblehead Neck (**25**); but equally instructive specimens can be obtained at many other points on our coast. It is also observable that the well-rounded pebbles are much smaller on the average than the angular blocks.

From these facts we draw the legitimate inference that the pebbles were all originally angular, and that the same abrasion which diminishes their size makes them round and smooth. A little reflection, too, shows that the rounding of the angular fragments is a natural and necessary result of their mutual collisions; for the angles are at the same time their weakest and most exposed points, and must wear off faster than the flat or concave surfaces.

The next specimen (**29**) shows how the softer parts of the rock-fragments are worn away more rapidly than the hard parts, the latter forming the salient portions of the rounded pebbles. Typical examples of well-rounded pebbles are also seen in the specimens from the beaches at Newport (**27–28**). Whether the forms are circular, spherical or oblong depends mainly upon the general shape of the original fragments, *i. e.*, upon the way in which the parent ledge or cliff breaks up.

The formation of rounded pebbles by abrasion is very beautifully illustrated by fragments of brick, coal, or glass (**26**) which have been worn smooth and round by being rolled about on the beach; for it is certain in the case of such specimens that they were originally rough and angular.

Having traced each pebble back to a larger angular rock-fragment, the question arises, Whence come these angular blocks? Behind the gravel-beach, or at its end, there is usually a cliff of rocks. As we approach this it is distinctly observable that the angular pebbles are more numerous, larger, and more angular; and a little observation shows that these are simply the blocks produced by jointing, and that the cliff is entirely composed of them. In other words, the cliff is a mass of natural masonry, which chemical agencies, the frost, and the sea are gradually disintegrating and removing. As soon as the blocks are brought within reach of the surf their mutual collisions make them rounder and smaller; and small, round pebbles, sand, and clay are the final result.

Where the waves can drive the shingle directly against the base of the cliff, this is gradually ground away in the same manner as the loose stones themselves, sometimes forming a cavern of considerable depth, but always leaving a smooth, hard surface, which is very characteristic, and contrasts strongly with the upper portion of the cliff, which is acted on only by the rain and frost. A good example of such a pebble-carved cliff may be seen behind the beach on the seaward side of Marblehead Neck.

The sea acts within very narrow limits vertically, a few feet or a few yards at most; but the coast-lines of the globe (including inland lakes and seas) have an aggregate length of more than 150,000 miles. Hence it is easy to see that the amount of solid rock ground to powder in the mill of the ocean-beach annually must be very considerable. Waves, cutting ever at the shore-line only,

act like an horizontal saw. The receding shore-cliff, therefore, leaves behind it an ever-increasing submarine platform which marks the amount of recession. See the photograph (**1**). The rate of this marine erosion and the form of the coast depend upon both the force of the waves and currents and the nature and structure of the rocks. The irregular coast of this region is due mainly to the fact that, on account of differences in composition and structure, the rocks vary greatly in the resistance which they offer to the action of the waves. The waves and currents not only have great power to break up and wear away the land, but also to transport the debris resulting from their action.

It is swept along the coast into some sheltered bay or carried out by the ebbing tide into deep water. These principles are well illustrated by the promontories and islands of Boston Harbor; and by the models (**21–24**), which should be studied in order, beginning on the left.

MECHANICAL EROSION — ON THE SURFACE OF THE LAND.

It is a familiar fact that after heavy rains the roadside rills carry along much sand and clay (which we know have been produced by the previous action of chemical forces), and also frequently small pebbles or gravel. It is easy to show that in all important respects the rills differ in size only from brooks and rivers; and the former afford us fine models of the systems of valleys worn out during the lapse of ages by rivers. The turbidity of rivers is often very evident, and in shallow

streams we can sometimes see the pebbles rolled along by the current.

Now here, just as on the beach, the collisions of rock-fragments are attended by mutual abrasion, sand and clay are formed, and the fragments become smaller and rounder. Our series of pebbles from the beach might be matched perfectly in the river-gravel. In mountain streams especially we may often observe that pebbles of a particular kind of rock become more numerous, larger, and more angular as we proceed up stream, until we reach the solid ledge from which they were derived, showing the same gradation as the beach pebbles when followed back to the parent cliff.

The pebbles, however, not only grind each other, but also the solid rocks which form the bed of the streams in many places, and these are gradually worn away. When the rocky bed is uneven and the current is swift, pebbles collect in hollows where eddies are formed, by which they are kept whirling and turning, and the hollow is deepened to a pot-hole, while the pebbles, the river's tools, are worn out at the same time.

By these observations we learn not only that running water carries away sand and clay already formed, but that it also has great power of grinding down hard rocks to sand and clay. The ocean is the common goal of nearly all rivers; and therefore the constant tendency of the rain falling upon the land is to break up the rocks by chemical and mechanical action and transport the debris into the sea.

The erosive power of water is most easily studied in ravines, gorges, and cañons, and especially in waterfalls. Every waterfall is slowly moving up stream, cutting its way back through the rocks over which the stream pours. Hence, while the gorge is deepened by the action of the stream on its bottom, it is also lengthened at the upper end by the recession of the escarpment. In many cases, as at Niagara, and in the examples illustrated by the photograph (**2**) and the model (**61**), the gorge is evidently the product chiefly of the cascade. By carefully observing the present rate of recession of a waterfall, the time required for the excavation of its gorge can be approximately determined; and in this way some of our most reliable estimates of the length of geological time have been reached. The different time-estimates for Niagara range from 5,000 to 40,000 years. But all our estimates are in harmony on the main points; viz., that erosion is a slow process and that geological time is immensely long.

The principal factors in stream-erosion are: (1) Hight above sea-level; for, of course, streams cannot cut below the level of the sea, and altitude is required to give them force or erosive power. (2) Amount of water. (3) Character and structure of the rocks. The valley shown in the next model (**62**) is characteristic of a moderately elevated country, the surface of which is exposed to the action of frost and a generous rainfall. The stream cuts down its bed, while the rain and frost wear down the whole face of the country, rounding off or bevelling the edges of the valleys. The strata are represented as horizontal, and such inequalities as appear in the slopes are due to the unequal hardness of the layers of rock. The companion model (**63**) and photograph of the Grand Cañon of the Colorado (**53**), on the other hand, show the deep, narrow valleys or cañons characteristic of a more elevated and much drier country. Cañons, as explained

on the labels, have their typical development where arid plateaus, like those of Utah, Colorado, New Mexico, and Arizona, are traversed by rivers deriving their water from distant mountains. The rivers, under these conditions, cut deep narrow trenches or cañons across the plateau; for the walls of the cañons, being but little exposed to the action of rain and frost, retain their upright form. In this connection, the visitor should examine the large relief map of the Grand Cañon of the Colorado and the High Plateau in the west window-space of Room B.

These stupendous examples of erosion are very impressive. It is necessary to remember, however, that the erosive power of streams is in most cases far inferior to that of rain and frost, because the latter act upon such vastly larger areas. But the transporting power of running water is very great; and carrying the products of chemical and mechanical erosion to the sea is, after all, the chief office of rivers, geologically considered.

The transporting power of a current varies as the sixth power of the velocity, which means that doubling the velocity increases the transporting power sixty-four times; and since the velocity depends upon the rate of fall or descent of the stream bed, it is clear that transportation as well as erosion will be most effective in the upper or mountainous parts of the rivers. This is well illustrated by the large photograph (**81**) of a mountain valley in Norway. It is evident that during the period of high water the floor of the valley is swept by a torrent carrying immense amounts of debris, the source of which is sufficiently manifest in the talus of shattered rocks heaped against the base of the cliffs and produced by the quiet action of rain and frost.

When, from any cause, such as a diminution of water or of slope or a broadening of its channel, the velocity of a stream is diminished, a large part of the debris which it carried or rolled along is deposited. The flood-plains of its lower courses (photograph **54**) and the delta at its mouth are formed of these deposits. The photograph (**30**) of the detrital cone at Silvaplana is a fine example of the fan-shaped deposit of debris, or delta, formed where a mountain torrent enters the quiet waters of a lake. The gradual formation of a delta at the mouth of a river flowing into the sea is illustrated by two models (**64–65**)

Rivers are continually uniting to form larger and larger streams; and thus the drainage of a wide area sometimes, as in the case of the Mississippi Valley, reaches the sea through a single mouth. By careful measurements made at the mouth of the Mississippi it has been shown that the 20,000,000,000,000 cubic feet of water discharged into the Gulf of Mexico annually carries with it no less than 7,500,000,000 cubic feet of sand, clay, and dissolved mineral matter; and this, spread over the whole basin of the Mississippi, would form a layer a little more than $\frac{1}{5,000}$ of a foot in thickness. So that we may conclude that the surface of the continent is being cut down on the average about *one foot* in *five thousand years*.

We turn next to the very important geological action of water in the solid state, as in glaciers and icebergs. The moisture precipitated from the atmosphere, and falling as rain, makes ordinary rivers; but falling in the form of snow in cold or elevated regions, where more snow falls than is melted, the excess accumulates and is gradually compacted to ice, which, like water, yields to the

enormous pressure of its own mass and flows toward lower levels. When the ice-river or glacier reaches the sea it breaks off in huge blocks, which float away as icebergs. Moving ice, like moving water, is a powerful agent of erosion; and the glacial marks or scratches observable upon the ledges everywhere in the Northern States and Canada attest the magnitude of the ice-action at a comparatively recent period. The photograph (**1**) of an elevated Alpine valley shows the birthplace or source of a glacier in the broad and deep accumulation of granular, half compacted snow or *névé*. This moves slowly but steadily down the steep slopes and is soon changed by pressure and repeated thawing and freezing to true glacier ice.

The next photograph (**26**) shows how the nearly perfect ice is broken and crushed in its movement over a steeper and more irregular slope. While the photograph of the Viesch Glacier (**2**) is a general view of a long, well-defined, typical, Alpine glacier from its source in the field of *névé* nearly to its lower limits, where the wasting of the ice by the sun and air just balances its downward movement. It shows how perfectly the ice-stream adapts itself to the serpentine form of the valley; and also the wonderful way in which it is fissured or crevassed in passing over and around the convex surfaces. The *lateral* moraines are distinctly shown along either edge of the glacier. These are bands or ridges of debris which has fallen upon the ice from the crumbling cliffs, or has been torn by the glacier itself from the base of the cliffs. Where two glaciers unite, as in the upper end of this view, the two adjacent lateral moraines are combined to form one *medial* moraine, which is shown here as a dark, serpentine ridge of debris extending down the middle of the glacier from the point of union to its lower limit.

An exceptionally fine development of medial moraines is afforded by the great Gorner Glacier and its numerous tributary glaciers descending from the Monte Rosa and Matterhorn range, as seen in the panorama from the Gorner Grat (**48**).

Model (**21**) shows, in some respects, a more complete system of Alpine glaciers, from the lofty snow-fields and *névé*, down along the glacier proper with its medial and lateral moraines, to the terminal moraine and the stream which issues from the lower end of the glacier. The relief map of the Mt. Blanc Range in section 47, Room B, is also of particular interest in this connection.

All the material carried on, in or under the ice is, of course, dropped at the lower end of the glacier and contributes to the formation of the terminal moraine. This immense accumulation of debris, which is essentially the delta of the glacial river, is pushed by the advance of the glacier into a steep, crescentic ridge.

The most important geological work accomplished by glaciers is the erosion of the rocks over which they move and the transportation of the debris in the different kinds of moraines. In existing glaciers, the transportation is very obvious, and the wearing or erosion also, where a temporary retreat of the ice exposes the rocky bed over which it has recently moved. For the rocks in such positions are always smooth and rounded and marked by grooves and scratches running in the direction in which the ice has moved The block of fine hard granite (**82,**