to the yielding and crushing of the crust, with the exception of such structural features as may have existed in the rocks before the crushing and uplifting took place.

From our present position, then, it is clear that mountains are the result of two distinct processes:—

1. The crust yields, in obedience to the *interior* forces originating in the retreat of the central heat—*igneous* agencies, and the altitude, *general* outline, and most of the internal structure of the chain are produced.

2. The grand and simple bulge thus formed is modified or *sculptured* by *exterior* or *aqueous* agencies, developing most of the external structural or relief features of the chain.

These two processes or stages have been very appropriately named mountain *formation* and mountain *sculpture*. It is the mountain *formation*, only, that interests us now, our present object being, especially, to trace the operation of the subterranean or igneous agencies. Hence it is unnecessary to consider farther, at this point, the forms or external structure of mountains.

If the earth's crust were homogeneous, *i. e.*, equally strong in all parts, the crushing and wrinkling would, of course, be uniformly distributed. The surface would be generally roughened, as in a withered apple, but no distinct or dominant lines of elevation would be formed. Therefore, in a complete explanation of the origin of mountains we must account not only for a force adequate in direction and intensity, but also for the existence of the relatively weak zones in the crust.

To do this satisfactorily it is necessary to call attention first to two of the most important characteristics of

mountain-ranges. (1) They are always composed of thick deposits of sedimentary or stratified rocks, and, usually, the size and other features of a mountain-system or range are proportional to the thickness of the sediments composing it; the thickness in most cases ranging from 20,000 to 60,000 feet. The section of the Alleghany Mountains (**48**) illustrates this important feature, and shows that, in consequence of the folding of the strata, a great part of the sediments is still below sea-level, and that their thickness exceeds the altitude of the mountains. The sedimentary rocks are, of course, formed below the level of the sea; and when they are squeezed horizontally and thickened vertically only a part of their mass is thus forced above sea-level.

(2) Mountain-ranges are usually, as shown in the introduction, near to and parallel with the shores of the ocean; if not of the existing ocean (Rocky Mountains, Andes, etc.), then of the ocean at the time the mountains were made (Alps, Ural Mountains, etc.).

These two features show that in their origin mountains are connected with the sea. For reasons which will be fully explained under the aqueous agencies, the thick accumulations of sediments of which mountains are formed can only be deposited in the marginal portions of the sea, following the coast-lines. Of course these belts of new sediments, at first, add little to the strength of the earth's crust; and before they become consolidated and strong they cause the interior heat of the earth to rise in and soften the underlying hard rocks. The zone of thick sediments parallel with the coast is thus gradually converted into a weak zone of the earth's crust, until finally it can no longer resist the growing horizontal pressure, but collapses, and the resulting mountain-range is added to the border of the continent.

The minor corrugations of the strata composing the earth's crust, the rock-folds or arches, so extensively developed in mountains, are, still more clearly than continents and mountain-ranges, the product of tangential compression. But the detailed explanations of their origin may be most conveniently considered in connection with the structural characteristics of the different kinds of folds, in the Guide to the Petrographic Collections. Faults, slaty cleavage, and other important structures incidental to the formation of mountains and resulting from the same great cause may be similarly treated. A vast amount and variety of geological structures are produced during the growth of a mountain-range; and it is to the mountains that the student in almost every department of geology most naturally turns.

EARTHQUAKES.

The great earth-movements of elevation and subsidence and mountain-formation are not always perfectly smooth and steady; but they are accompanied by breaking, slipping and crushing of the rocks now and then; and, as a result of the shocks thus produced a swift vibratory movement or jar, which we know as an *earthquake*, spreads through the earth's crust.

Earthquakes are not only associated with movements of the earth's crust, but also with volcanic action; and the fact that volcanoes emit vast volumes of steam and other vapors with explosive violence makes it probable that earthquakes in volcanic regions are often due to the sudden expansion or condensation of steam; the earthquake, in this case, resembling the jar produced by the explosion of a keg of gunpowder buried in the earth.

An earthquake, whether due to an explosion or to the rupture or slipping of the rocks, is always, at its point of origin or focus, essentially a shock or blow. This primary shock or impulse causes a series of elastic vibrations or waves which spread out in all directions, as shown in the diagram on the chart (**61**), swinging the rocks to and fro through a few inches or a few feet and moving with a velocity of from 10 to 150 miles per minute. The point directly over the focus, where these vibrations first reach the surface, is called the epicentrum; and from this the shock spreads along the surface in an ever-widening circle. The direction of movement or shock is vertically upward at the epicentrum; but, as the radiating lines and arrows in the diagram show, the direction becomes more and more horizontal as the distance from the epicentrum increases. The tendency, therefore, is to throw vertically upward, or to crush, structures near the epicentrum, and to move horizontally or overthrow those remote from that point. It is by attention to these features that the position of the epicentrum and direction of movement are determined. The extremely sudden and violent to-and-fro movements or vibrations tend to form cracks or fissures in the earth, and in any structure resting upon it, at right angles to the direction of wave-movement, *i. e.*, at right angles to the radiating lines and arrows in the figure. Such earthquake-fractures are seen in the photograph. By observing where the perpendiculars to these fractures in different localities would meet if extended downwards in the earth, the position, depth and form of the earthquake focus are determined.

The distribution of the regions affected by earthquakes in recent times is indicated by the red shading on the small map of the world (**62**). The shading is darker in proportion to the force and frequency of the shocks. The black dots represent active volcanoes, and serve to show to what extent earthquakes are associated with volcanic phenomena.

VOLCANIC ACTION.

Under this head we properly consider all those agencies concerned in transferring *hot* materials from the earth's interior *to* or *towards* its surface. Every kind of volcanic activity requires a tube or opening leading up from deep-seated portions of the crust to or toward the opening.

This opening or conduit must usually, if not always, originate as a fissure or crack in the earth's crust. Eruptions may occur at all points or many points along an extended fissure, but often only at the widest part or at the intersection of two fissures, and thus a tube is formed.

The heated ejectamenta may be *solid* (stones, cinders, sand and dust), *liquid* (molten lava and water), or *gaseous* (steam and various acid vapors). Of these various products, the molten lava or liquid rock is by far the most characteristic and important.

A volcano is, then, fundamentally, a hole in the ground from which are ejected, in a highly heated condition, liquid and fragmental lavas and various gases or vapors. The accumulation of the lavas around the vent builds up the volcanic *cone*, with a cup-shaped crater at the top; but where the lava is sufficiently liquid it spreads out horizontally, forming a volcanic bed or

sheet. While the lava which fails to reach the surface cools and solidifies in the fissures or conduits, formin *dikes*. Thus we have as the products of volcanic action, two great classes of igneous rocks:—(1) The volcanic rocks (**21–31**), which have cooled rapidly, under little pressure, and are usually light, porous, imperfectly crystalline and largely fragmental; and (2) the plutonic or dike rocks (**41–44**), which have cooled slowly and under great pressure, and are, as a rule, dense and crystalline.

The aspects of a typical volcano in a nearly quiescent state, and during a great eruption, are shown in the views of Vesuvius (**1**); while the accompanying diagram illustrates the general relations of the volcanic cone and conduit or fissure to the earth's crust, which is represented as composed of stratified or sedimentary rocks in the upper part and massive or igneous rocks in the lower part.

Volcanic eruptions may be divided into two great types, viz., the *quiet* and the *explosive*. In the first, the lava is very fluid and flows out quietly from the central crater or through lateral fissures, with few explosions and little fragmental material; while in the second the material is largely blown out in the form of dust and fragments by explosions of steam, accompanied by violent earthquakes. The Hawaiian volcanoes are perhaps the best examples of the first class, and the Javanese volcanoes of the second class.

The form of a volcanic cone evidently depends upon the character of the eruptions and the fluidity of the lava, and especially upon the relative proportions of lava and fragmental materials. Thus, Etna (**83**, section 3) is built up chiefly of rather fluid lava, which spreads far from the vent, so that it is a broad low mound with very gentle slopes; while Vesuvius (**87**), consisting largely of fragments and dust formed by the violent explosions accompanying its eruptions, and which fall mainly in the immediate vicinity of the crater, presents the more conical form and steeper slopes shown in the photographs already referred to.

Every important volcanic cone is the product of intermittent eruptions during a long period of years, and consequently must consist of many successive layers of lava and of fragments or volcanic tuff, all sloping from the central orifice or crater. This normal structure of a cone is shown in the diagram accompanying the photograph of Monte Somma and the summit of Vesuvius (**2**). The summit of Vesuvius, shows the recently formed cinder-cone, the steam and acid vapors escaping from the lava, and, on the left, the contorted, rope-like structure characteristic of most lava-streams. This is also shown, together with the steam holes or vesicles formed by the expansion of steam in the liquid lava, in the large specimen (**30**), which is from the flow (1872) represented in the general view of Vesuvius in a state of active eruption (**1**).

Eruptions usually occur not only from the summit-crater of the volcano, but also often from lateral fissures. By the enormous hydrostatic pressure exerted by the liquid lava in the main crater and its conduit or throat the cone is burst open, and fissures are formed radiating from the crater. These cracks are filled with lava, forming dikes which intersect the successive layers of lava, so as to bind them together and strengthen the

volcano as a whole. Through these fissures, when first formed, the principal streams of lava often pass; and upon them subordinate craters and cones are finally formed. These smaller cones, appearing like pimples on the slopes of the main cone, are called monticules. There are about 600 monticules on the slopes of Etna, only a few of the larger ones being shown in the model of that volcano (**83**, section 3). From one of these on the south side of Etna descended the great lava-flow of 1669, which overwhelmed fourteen towns and villages and flowed into the sea.

The great depression in the eastern side of Etna, called the Val del Bove, and shown in the model, is probably due to a subsidence into a subterranean cavity formed by the enormous outflows of lava which have built up this gigantic cone; although it may possibly be due to some great explosion which has blown out the whole side of the volcano.

The immense amount of fragmental material ejected during some explosive eruptions with such force, or of such fineness as to be carried beyond the limits of the volcano itself, is clearly illustrated by the buried city of Pompeii. The exhumed ruins of this Roman town are shown in the photograph (**48**), with Vesuvius, the cause of the disaster, in the back ground. The city is several miles from the base of the volcano, and its site has not been covered by the molten lavas within historic times; but during the first historic eruption of Vesuvius, in the year 79, the whole floor and part of the wall of the ancient crater were blown away and Pompeii and the surrounding country were deeply buried under the volcanic dust and fragments of pumice.

The relief-map or model of Vesuvius (**87**) shows clearly how large a part of the rim or wall of the ancient crater was blown away at this time; and, also, in the darker color of the western and southern slopes, how extensive and wide-spread the subsequent out-flows of lava have been. The main, central cone of Vesuvius, some 1800 feet high, had no existence before the great eruption of 79, but is wholly made up of the dust and fragments and liquid lava thrown out during that and later eruptions.

Some of the principal events in the history of an active volcano, and the influence of its lava-streams upon the drainage and general topography of the country, are illustrated by the small models (**81–82**, section 3). The details of these are, however, sufficiently explained on the descriptive labels.

The small map of the world (**32**) shows the general distribution of volcanic phenomena at the present time. Each red dot represents an important cone or group of cones. The important feature of the distribution is that the active volcanoes of the globe, with a very few exceptions, are all on islands or on the margins of the continents. It is especially noticeable that the Pacific Ocean is bordered by a nearly continuous chain of volcanoes, from Patagonia to Behring's Strait, and from Behring's Strait to New Zealand.

Geologists have been able to show with much probability that this association of volcanoes with the coast-lines and the sea has existed during the whole of geological time. Thus, wherever volcanic rocks are found in the interior of the continents we have reason to believe that at the time of their eruption they were in or near the sea; the shore-line having subsequently receded in consequence of the constant vertical oscillations of the earth's crust.

Compared with the whole of geological history, volcanoes are short-lived. Their eruptions culminate, and then become fewer and weaker, and finally cease altogether. Erosion then rapidly wears away the more exposed portions of the volcanic mass; and by the time the shore-line has receded so as to leave it in the interior of the continent, the volcano is permanently extinct and has lost its characteristic form.

Geologists are still in doubt as to the cause of the association of active craters with the sea, and it remains to be determined how far, if at all, volcanic action depends upon access of the waters of the ocean to the highly heated subterranean regions. In fact, the whole question as to the exact cause of volcanic action is still unsettled.

Volcanic phenomena may be classed as primary, where attended by eruptions of liquid or solid lava, and secondary, where no lava is ejected, but only hot water and heated vapors and gases. The secondary accompany the primary phenomena and usually continue long after the outflows of lava have ceased and the volcano is otherwise extinct. Or they may exist quite independently of outflows of lava, where heat has been generated through rock-crushing by horizontal pressure, as already explained. But thick flows of lava remain hot in the interior for an incalculable time; and the secondary phenomena, including geysers, hot springs and solfataras, are due chiefly to the percolation of water through these heated masses. Solfataras exist where heated vapors, and especially sulphurous vapors, escape from the rocks. Deposits of sulphur, sal ammoniac, and other minerals are often formed about the vents. The specimen of sulphur (**45**) is from the Solfatara near Naples, Italy.

The escape of hot water gives rise to thermal springs; and when the water is very hot, so that violent eruptions of water take place periodically, the hot spring becomes a geyser. The thermal water, under the great pressure existing at considerable depths, decomposes the heated rocks through which it flows and large amounts of various minerals go into solution; and then, as the water escapes toward the surface, and its temperature and pressure are diminished, the dissolved minerals are largely deposited on the walls of the fissures through which it flows, until, finally, the fissures are completely filled and the water forced to seek a new outlet. In this way the various kinds of mineral veins are formed; and it has been conclusively proved that metalliferous and other veins are being made in this way at the present time, in California, Nevada, and other localities.

Where the thermal water issues on the surface, a farther portion of the dissolved minerals is often deposited, building up very characteristic masses which are called tufas. The substances most commonly deposited in this way are silica and carbonate of lime, forming siliceous tufa (**46**) and calcareous tufa (**47**). See also the photograph (**49**).

METAMORPHISM.

We have seen that the interior heat of the earth is slowly but steadily diminishing, and that this secular

cooling of the earth's interior probably contributes in an important degree to the development of the enormous tangential pressure known to exist in the earth's crust; also that this pressure is the chief agent in (1) determining the oscillations of the earth's crust and the distribution of land and sea, and (2) the formation of mountains, with all the attendant phenomena of rock-folds, faults, earthquakes, etc. Again, we have observed that the loss of the subterranean heat by conduction is supplemented in an important measure by volcanic action, or the transfer of heated matter, especially molten lava and water, from the earth's interior to the surface, giving rise, in its primary stages, to the great class of eruptive or igneous rocks, and, in its secondary stages, where heat coöperates with water, to many kinds of vein-rocks and tufas.

But the geological work of the subterranean heat does not end here; for it invades the stratified or sedimentary rocks, formed by the action of water alone on the earth's surface, and causes various important changes in composition and structure. These aqueous rocks are, for the most part, when first formed, deposits of gravel, sand, mud, shells, etc.; imperfectly consolidated and wholly uncrystalline. After their formation, as will be more fully explained elsewhere, they are consolidated and otherwise changed by heat, pressure and chemical action. All these changes are properly metamorphic; although this term is very generally restricted to the processes resulting in the crystallization of the sedimentary rocks. The exact causes of metamorphism are not definitely known in many cases, but it is certain that heat is usually a chief agent, 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.