matter almost wholly, intact. Thus, in the tooth of a mastodon (another extinct elephant) from Post-tertiary beds (**50**), the cetacean bones from the Miocene strata of Virginia (**46, 48**), and the teeth of gigantic extinct sharks from the Eocene phosphate beds of South Carolina (**42–43**), we have still not only the original phosphate of lime (the organic form of the mineral apatite) essentially intact, but also to some extent the original animal matter. In the large Miocene shells (**47, 49**), which may be regarded as representing a very large proportion of both fossil shells and corals, the animal matter has entirely disappeared, but the original mineral matter (carbonate of lime) still remains.

2. *Original composition completely changed, but form and structure preserved.*—All kinds of fossils are commonly called petrifactions; but only those preserved in this second way are truly petrified, *i.e.*, turned to stone. "Petrified wood is the best illustration, and in a good specimen, not only the external form of the wood, not only its general structure—bark, wood, radiating silver-grain, and concentric rings of growth—are discernible, but even the microscopic cellular structure of the wood, and the exquisite sculpturing of the cell-walls, are perfectly preserved, so that the kind of wood, may often be determined by the microscope with the utmost certainty. Yet not one particle of the organic matter of the wood remains. It has been entirely replaced by mineral matter; usually by some form of silica. The same is true of the shells and bones of animals."—Le Conte.

The petrified or silicified wood is well represented by the large specimen (**81**) on the bottom shelf of the third

section and the smaller specimens (**1, 8**) on the top shelf of the fourth section. Especially instructive are the comparatively recent specimens from the Geyser district of the Yellowstone National Park (**7, 9**). These are still composed in part of the original woody matter; but are well incrusted and permeated by the petrifying silica; and illustrate the petrifying process.

We must imagine the wood as immersed in alkaline water holding silica in solution. The wood gradually becomes saturated with the solution of silica (water-logged) the water filling not only the spaces between the vegetable cells, but penetrating the cells themselves. The decomposition of the protoplasm gives rise to acids, which neutralize the alkaline solvent of the silica and cause its precipitation, each minute particle of organic matter, as it decays, being replaced by an equivalent portion of silica. Afterwards the more durable woody walls of the cells are slowly replaced by silica of slightly different texture or color and the petrifaction is complete.

A very large proportion of the shells (**5**) and corals (**6**) found in the older limestones or calcareous strata have been silicified; and acquiring thus the hardness and durability of quartz, they are left in relief on the weathered surface of the rock. Among other petrifying substances, besides silica, are iron oxide (**2**) and iron sulphide (**3–4**).

3. *Original composition and structure both obliterated, and form alone preserved.*—This occurs most commonly with shells, although fossil trees are also often good illustrations. The general result is accomplished in several ways: (*a*) The shell after being buried in the sediment may be completely dissolved by percolating water,

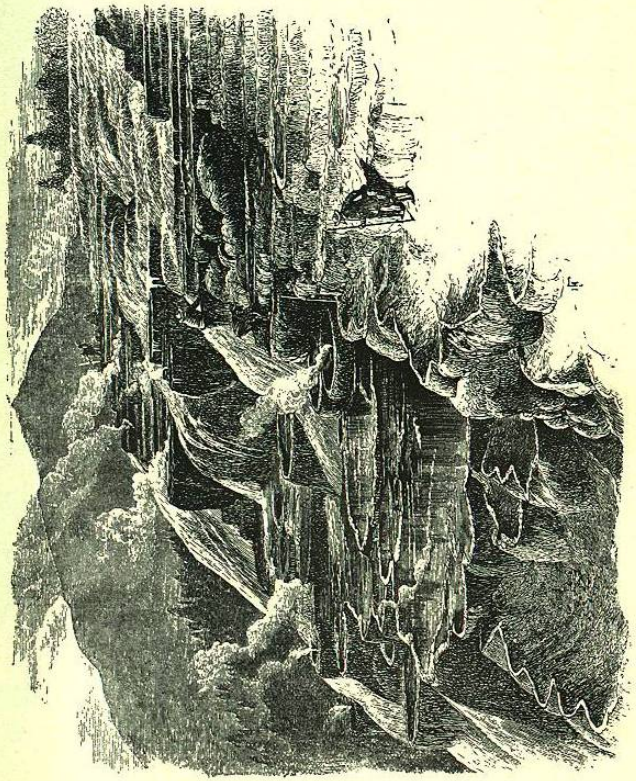
leaving a *mold* of its external form. The mold or impression of an egg-shell in eolian limestone from Bermuda (**24**) is a clear illustration, although the shell has not been entirely removed in this case. The piece of highly fossiliferous rock from North Carolina (**25**) shows many thin molds of bivalve shells. The large specimen on the bottom shelf of section 3 (**82**) shows deep impressions resembling horse-tracks, which are really due to the weathering out of a fossilized marine plant; and the adjacent specimens (**83–84**) are also good examples of the molds of corals and of crinoid stems. (*b*) The mold may subsequently be filled by the infiltration of finer sediment forming a *cast* of the exterior of the shell. This phase is best illustrated by the fossil trees (**31–32**) from the Carboniferous formation, the large specimen from the celebrated section at South Joggins, Nova Scotia, which is in the Vestibule, on the left side of the main stairs, being a particularly fine example. These are trees of three different species which have been buried while standing erectly, by the rapid deposition of mud and sand; and have then gradually decayed, leaving cylindrical holes or molds in the slowly hardening sediment, which have been subsequently filled by fine silt washed in by the water, forming these natural casts, which show so perfectly the external form of the trees, but are entirely structureless within. (*c*) The shell, before its solution, may have been filled with mud, as dead shells usually are; and if the shell itself is then dissolved away, we have a cast of its interior enclosed in a mold of its exterior. The specimens show these very common internal casts still in the rock (**22**) and also removed from it

(**21, 29–30**). The section of a large ammonite shell (**62**, section 3) is especially interesting because only the large outer or living chamber has been filled with mud, which has hardened in it, the smaller chambers behind this all the way around the coil being partially filled with silica deposited from solution and not simply washed in as the mud was. In the smaller shell (**27**) of the same kind all the chambers are filled with the hardened mud, and the shell has been subsequently removed. The large univalve shell (**29**) is interesting because only a part of the shell has been worn or dissolved away from the cast. The crayfish incrusted with iron oxide from the water of a chalybeate spring (**23**), although not strictly a natural specimen, is interesting as showing another way in which molds of the exterior may be formed. The impressions of fucoids (**26, 28**) often observed in the strata are to be classed with the fossil trees as exterior casts.

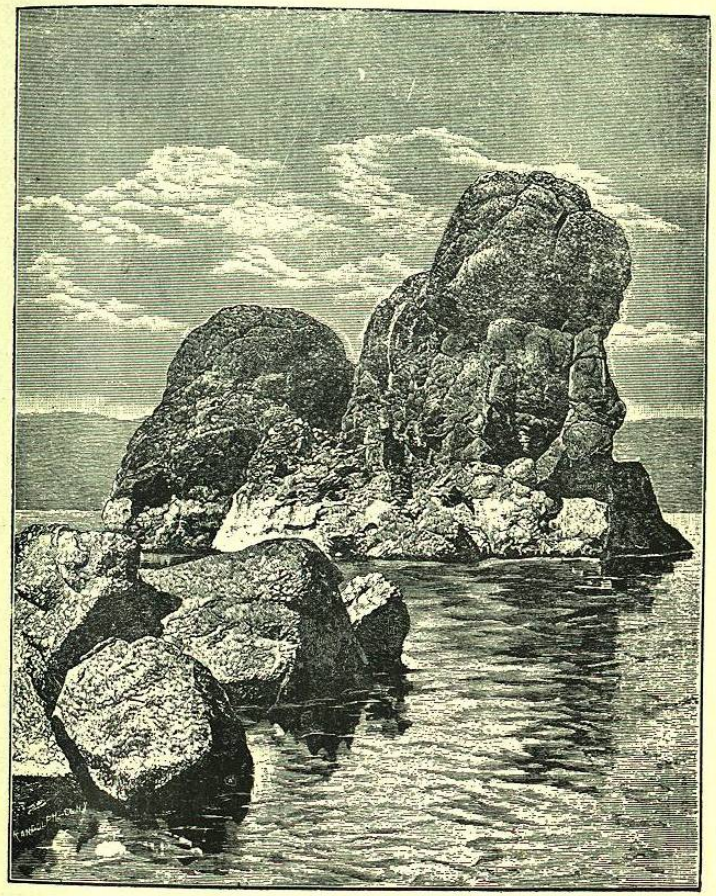
Forms of Tufa deposits. — We have already seen that the interesting rocks known as tufas are formed when certain minerals,—especially silica, carbonate of lime, and iron oxide — are deposited from solution, not over the bottom of a sea or lake forming regular strata; but around the outlet of a mineral spring, or along the stream which it forms, or on the margin of a lake whose waters are wasting by evaporation, forming rock masses which are not plainly or regularly stratified, but present other and very characteristic structural features. These are well illustrated by the specimens of calcareous and siliceous tufas in this section. The first specimens to be noticed (**23, 28, 62**) are the typical examples of calca-

reous tufa, which are formed so abundantly by the incrustation of vegetable forms — moss, grass, reeds, etc.; the subsequent decay of the organic matter leaving an exceedingly light and porous mineral network. These specimens might have been included with the illustrations of fossilization, the composition and structure of the plants being entirely obliterated and the form only imperfectly preserved. The thinolite tufa from the ancient and elevated beaches encircling the alkaline lakes of the Great Basin (**63–64**) is an exceptionally interesting variety of calcareous tufa, on account of being still more distinctly pseudomorphic in character. Its seemingly crystalline structure is supposed to be due to the fact that it was first formed by the abundant crystallization of sulphate of sodium from the waters of the lake, this salt being afterwards replaced by carbonate of lime. A third and quite distinct type of tufa is where the form is original and independent of foreign objects, being determined simply by the way in which the mineral water issues from the spring or geyser and the conditions of its evaporation. These forms, which are extremely varied and interesting, often imitating such organic growths as corals, fungi, etc., and constituting one of the chief attractions of the localities in which they occur, are quite well represented by the other specimens of calcareous tufa from the Great Basin (**61**) and Vermont (**49**), and the siliceous tufa from the geysers of the Yellowstone Park (**41–42, 45–47**).

Time required for the Formation of Stratified Rocks.—Many attempts have been made to determine the time required for the deposition of any given thick-



Tufa basins at Mammoth Hot Springs of Gardiner's River, Yellowstone National Park.



Tufa domes in Pyramid Lake, Nevada.

ness of stratified rocks. Of course, only roughly approximate results can be hoped for in most cases; but these are at least sufficient to make it certain that geological time is very long. The average relative rate of growth of different kinds of sediment is, however, less open to doubt, for we have already seen that coarse sediments like gravel and sand accumulate much more rapidly than finer sediments like clay and limestone; and we are sometimes able to compare these two classes of rocks on a very large scale.

Thus, during what is known as the Paleozoic era, a sea extended from the Blue Ridge to the Rocky Mountains. Along the eastern margin of this sea, where the Alleghany Mountains now stand, sediments—chiefly conglomerate and sandstone, with some slate and less limestone—accumulated to a thickness of nearly 40,000 feet. Toward the west, away from the old shore line, the coarse sediments gradually die out, and the formations become finer and thinner. In western Ohio and Indiana, slate and limestone predominate; while in the central part of the ancient sea, in Illinois and Missouri, the Paleozoic sediments are almost wholly limestones, and have a thickness of only 4,000 to 5,000 feet. In other words, while one foot of limestone was forming in the Mississippi Valley, eight to ten feet of coarser sediments were deposited in Pennsylvania.

The interesting specimens (**81–82**) from Silver Cay Reef, off Turk's Island, in the West Indies, showing considerable growths of coral on a large bell, olive-jar and decanter, which were recovered in 1857 from the wreck of a vessel supposed to be the British frigate Severn, lost at this place in 1793, are admirable examples of the kind of evidence upon which estimates of the time re-

quired for the formation of limestone are based. We have here in sixty-four years coral growths upwards of a foot in thickness.

But the formation of limestone strata on this reef must be much less rapid than this; for we must remember that the growth of corals on a reef is much like that of plants in a garden, isolated coral stalks and masses standing here and there and growing upwards rapidly while the intervening ground may be nearly or quite bare of living coral. When the polyps die, the brittle coral is broken up by the action of the surf and the fragments and coral sand are strewn over the general surface of the reef, which is thus gradually elevated as a whole.

The best estimates show that coral-reefs rise—*i.e.*, limestones are formed on them—at the rate of about one foot in two hundred years. But coral limestones grow much more rapidly than limestones in general. Sandstones sometimes accumulate so rapidly that trees are buried before they have time to decay and fall. This is the history of the Carboniferous tree in the Vestibule, on the left side of the main stairs. It is from the section on the South Joggins shore in Nova Scotia, where no fewer than seventy coal seams and old land surfaces, often with buried forests, have been observed alternating with marine strata. Every buried forest, like a coal-bed, represents a land surface, and proves a subsidence of the land; and in some cases repeated oscillations of the earth's crust may be proved in this way.

The mud deposited by the annual overflow of the Nile is forty feet thick near the ancient city of Memphis; and the pedestal of the statue of Rameses II., believed to have been erected B. C. 1361, is buried to a depth of nine feet four inches, indicating that 13,500 years have elapsed since the Nile began to spread its mud over the sands of the desert.

The specimen of laminated glacial clay (**65**) is of special interest in this connection, since it is probable that one complete layer was deposited annually. During the recession of the great ice-sheet, the melting of the ice and the resulting floods of water were intermittent, varying with the seasons. During the summer, the clay in the drift was washed down rapidly and spread over the bottom of a glacial lake, forming one of the gray layers seen in the specimen; but with the advent of the long winter the flow of water nearly ceased, the lake became covered with a thick sheet of ice; and during this period of perfect tranquillity the finest silt suspended in the water, together with any organic matter that may have been present, slowly settled, forming the brown line separating each layer of gray clay from the next. It is believed that the banded sandstones and slates (see section 1) have a similar significance, recording periodic deposition. It is not necessary, however, to suppose that the layers are always, like the rings on the section of a tree, strictly annual deposits; but they testify rather to alternating flood and drouth; or, possibly, in the case of some marine sediments, to the ebb and flow of the tide.

But the greatest difficulty in estimating the time required for the formation of any series of strata arises from the fact that we cannot usually even guess at the length of the periods when the deposition has been partially or wholly interrupted. Now and then, however, we find evidence that these periods may be very long. A layer of fossil shells in sandstone or slate (**66**) or on the surface of the rock (**67**) proves an interruption of mechanical deposition. Beds of coal, fossil forests, and other indications of land surfaces are still more conclusive. The interposition of strata (page 193) proves a prolonged interruption of deposition over the area not covered by the interposed bed. But the most important of all evidence is that afforded by unconformity (page 194); and the length of the lost interval

between the two formations is measured approximately by the erosion of the older.

The old gun (**87**), the bottles (**84–85**), and other objects (**83, 86**), in this section, with oysters and other marine organisms attached, have been dredged at different points along our coast; and show very plainly that in these localities the deposition of the ordinary mechanical sediments is practically at a stand-still, for otherwise these objects would have become buried in the sand or mud before there was time for several generations of shells and other animals to grow upon them.

ORIGINAL STRUCTURES OF ERUPTIVE ROCKS.

The structures of this class are naturally divisible into those pertaining to the plutonic rocks or dikes and those pertaining to the volcanic rocks or lava-flows.

Dikes.

The term *dike* is a general name for all masses of eruptive rocks that have cooled and solidified in fissures or cavities in the earth's crust. But the name is commonly restricted to the more regular, wall-like masses, such as are represented by the first model (**1**), and by several of the specimens, and can be observed to good advantage in many of the ledges about Boston; and the plutonic eruptions of extremely irregular outline, such as the granitic rocks usually present, as shown in the next model (**2**), are known simply as eruptive masses.

The propriety of this distinction is apparent when we consider the origin of *dike* as a geological term. It was first used

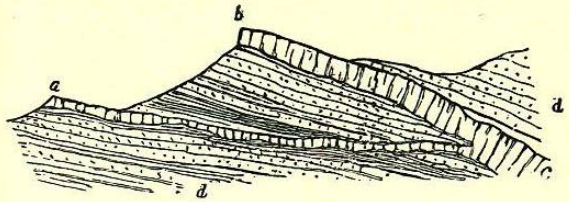
in this sense in southern Scotland, where almost any kind of a wall or barrier is called a dike. The dikes traverse the different stratified formations like gigantic walls, which are often encountered by the coal-miners, and on the surface are frequently left in relief by the erosion of the softer enclosing rock, so that in the west of Scotland, especially, they are actually made use of for enclosures. In other cases the dike has decayed faster than the enclosing rock, and its position is marked by a ditch-like depression. The narrow, straight, and perpendicular clefts or chasms often observed on our coast are due to the removal of the wall-like dikes by the action of the waves. Dikes are sometimes mere sheets of rock, traceable for a few yards only; and they range in size from that up to those a hundred feet or more in width, and traceable for scores of miles across the country, their outcrops forming prominent ridges. The sides of dikes are often as parallel and straight as those of built walls, the resemblance to human workmanship being hightened by the numerous joints which, intersecting each other along the face of a dike, remind us of well-fitted masonry.

Forms of Dikes.—A dike is essentially a casting. Melted rock is forced up from the heated interior into a cavity or crack in the earth's crust, cools and solidifies there, and, like a metallic casting, assumes the form of the fissure or mold. In other words, the form of the dike is exactly that of the fissure into which the lava was injected. Now the forms of fissures depend partly upon the nature of the force that produces them, but very largely upon the structure—and especially the joint-structure—of the enclosing rocks. Nearly all rocks are traversed by planes of division or cracks called joints, which usually run in several directions, dividing the rock into blocks. And it is probable that dike-fissures are

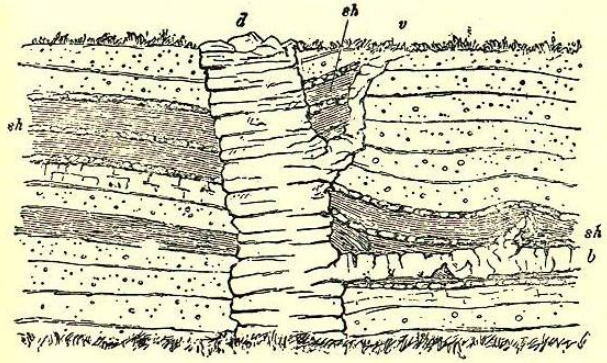
most commonly produced, not by breaking the rocks anew, but by opening or widening the pre-existing joint-cracks. Hence dikes formed in rocks possessing a well-developed and regular joint-structure, such as the slate (**3**) and conglomerate (**4**) in the vicinity of Boston, and most kinds of sedimentary rocks, must of necessity be regular and wall-like in form; and, *vice versa*, the irregular jointing or absence of jointing often observed in granite (**5**) and other massive eruptive rocks gives rise to more sinuous, branching, and variable dikes.

This principle is abundantly and admirably illustrated in the vicinity of Boston, particularly in the slate quarries of Somerville, and in the large puddingstone quarry in Roxbury. The general dependence of the dikes upon the joint-structure is proved by the facts that, as may be readily observed in the quarries, the dikes, like the joints, are normally vertical or highly inclined, and that they are usually parallel with the principal systems of joints in each district. In the models (**1–2**) the faintly incised lines represent the joint-planes; while the stratification of the first is shown by the horizontal stripes of color. The regular and typical dikes are often branching, it is true, but in a regular and systematic manner, as shown in the model. The main dike or a branch of it may pass horizontally between the strata for a long distance, or it may approach the surface by a zigzag course, alternating in direction between the bedding-planes and joint-planes or between two sets of joint-planes.

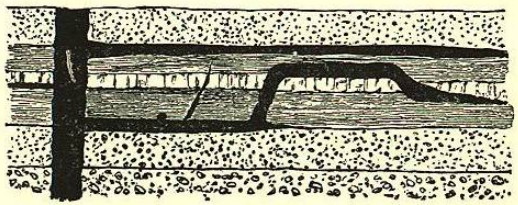
When the dike-fissures are formed by breaking the rocks anew at the time of the eruption, it will be readily understood that if the breaking force acts slowly, so as to be influenced by all the inequalities of texture and structure, the fractures or fissures will usually be far more irregular than if the strain be developed suddenly, as during an earthquake; on the same principle that a bullet thrown by the hand will break a pane of glass



Intrusive sheets of basalt. Edinburgh. *a*. Sheet forming St. Leonard's Crags. *b*. Sheet forming Salisbury Crags. *c*. United sheet forming Samson's Ribs. The enclosing strata are Carboniferous sandstones and shales.



Dike (*d*), rising along a fault, through sandstone and shale (*sh*); and giving off an irregular branch (*v*), and an intrusive sheet (*b*).



Sheets of basalt intruded between beds of sandstone, clay and limestone. (Island of Skye.)

more irregularly than one fired from a gun. In this way we can explain the occurrence of trap dikes of regular form in granite (**25–27**), conglomerate, and other coarse-grained rocks. The trap dikes in marble from Smithfield, R. I., (**21–23**) have the same significance; although they have been somewhat broken and faulted subsequently to their formation.

The water-worn fragment or pebble of syenite from Marblehead Neck (**24**) is divided by a tiny branching dike of trap, a small but very clear example of a dike enclosing or surrounding a relatively large mass of the bordering or wall rock.

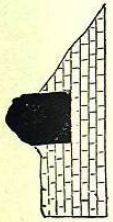
The specimen from Mount Royal (**51**) shows two approximately parallel dikes of trap cutting obliquely across a bed of Trenton limestone, and may be regarded as illustrating the occurrence of dikes in systems after the manner of the joint-planes. The irregularly branching forms of dikes are particularly well illustrated by the small dikes of syenite in diorite from Nahant (**82–83**) and Marblehead (**66**).

Structure of Dikes. — The rock traversed by a dike is called the *country* or *wall* rock. Fragments of this are often torn off by the igneous material and become enclosed in the latter. Such enclosed fragments partially or wholly detached are represented in certain of the dikes shown in the model (**2**). They are sometimes so numerous as to form the main part of the dike, which then, since the fragments are necessarily angular, often assumes the aspect of a breccia, in which the enclosed fragments form the pebbles and the eruptive rock the cement. The granite (**61**, **81**), and syenite (**66**) eruptive through the diorite in Marblehead, Salem, and many other districts

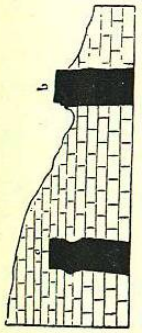
about Boston afford magnificent examples not only of dikes crowded with enclosed fragments, but of nearly every kind of irregularity of both form and structure to which dikes are subject.

The enclosed fragments in dikes sometimes throw important light upon the relative positions and ages of the rocks traversed by the dikes. Thus the well-rounded quartzite pebble in the coarsely crystalline trap from Somerville (**44**) proves that although at the surface the country rock is slate, at some depth below the surface the dike must break through beds of conglomerate from which the melted trap has picked this pebble on its way up through the fissure, and hence that the conglomerate probably underlies the Somerville slate. Other instances of the same kind have been observed at Nantasket.

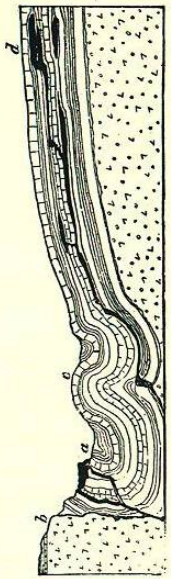
The enclosed fragments afford the only important exception to the rule that dikes are homogeneous in composition; *i.e.*, in the same dike we can usually find — from end to end, from side to side, and probably from top to bottom — no essential difference in composition. This homogeneity is well illustrated by several of the specimens. But there is often a marked contrast in *texture* between different parts of a dike and especially between the sides and central portion. The liquid rock loses heat most rapidly where it is in contact with the cold walls of the fissure, and solidifies before it has time to crystallize, remaining compact and sometimes even glassy; while in the middle of the dike, unless it is very narrow, it cools so slowly as to develop a distinctly crystalline texture. There is no abrupt change in texture, but a gradual passage from the compact border to the coarsely crystalline or porphyritic middle portion. It is obvious that a sim-



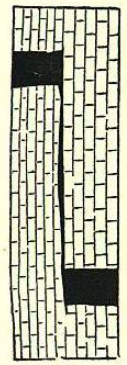
Ideal cross-section of a flat-bottomed dike.



Ideal cross-section of flat-topped dikes.
a. Before denudation; *b*. after denudation.



Section showing the intrusive beds of basalt in Mt. Evarts. Yellowstone National Park. *a*. Yellowstone River; *b*. fault; *c*. crumpled strata; *d*. Mt. Evarts ridge and basaltic sheets.



Explanation of flat-edged dikes.

ilar gradation in texture must exist between the top and bottom of a dike. It is difficult to observe this gradation between the wall and center in small dikes, because they are essentially compact throughout, but it is slightly indicated in one of the little dikes from Marblehead (**25**); and the two hand specimens of trap (**52–53**) represent the wall and center portions respectively of a dike forty feet wide on Marblehead Neck.

Enclosed fragments of the wall rock have sometimes exerted a similar chilling influence upon the contiguous igneous rock; so that they are immediately enveloped by a layer which is much more compact than the general mass. This is very clearly shown by the quartzite pebble already referred to (**44**) in the coarse Somerville trap. It is usually observed, also, that while the main part of a large dike is distinctly or coarsely crystalline, the small, branch dikes running off from it are of a very compact texture. This is well illustrated by the two specimens from a large dike in Somerville. The black, coarse-grained specimen (**46**) represents the main part of the dike, and the small, fine-grained or compact dike in slate (**49**) is one of the narrow branches extending out into the slate. Dikes, especially near the original surface, or where they have been formed under little pressure, are sometimes vesicular (**28**), after the manner of ordinary lavas; or the steam-holes may be filled with secondary minerals, making the rock amygdaloidal (**29**).

Somewhat related to the gradation in texture is the flow-structure parallel with the walls occasionally observed in dikes. This structure, which sometimes takes the form of a distinct banding or striping, is well developed in some of the dark, crystalline diabase of Nahant and the outer islands of Boston Harbor (**65**). It clearly in-