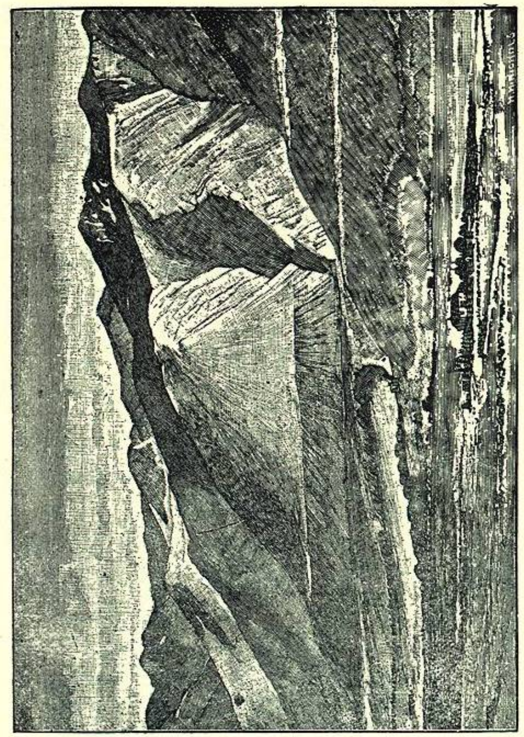
The faulted pebble of quartzite (**61**) is from the Roxbury pudding stone. The remarkably regular joint-planes of that rock frequently divide the pebbles; and it is a common observation that the two parts of the same pebble no longer correspond in position, but show a slip or displacement in the plane of the fracture.

The large piece of interstratified slate and sandstone from Brighton (**66**) shows one distinct and several indistinct faults, all characterized by a normal degree of irregularity. But the small dike in white marble from Smithfield, R. I. (**67**), has been dislocated beyond any possible restoration. The numerous dikes of the Boston Basin afford many admirable illustrations of different kinds of faults; but undoubtedly the best single example is the dike on the Swampscott Shore which is represented, on a scale of twelve feet to the inch, in the drawing (**24**). It is perfectly exposed for a length of nearly four hundred feet, and is broken in that distance by no fewer than thirty-six distinct faults.

The wooden models on the first two shelves illustrate some of the more general relations of faults and of systems of faults, and especially the relations of faults to erosion. The ages of faults are determined in the same ways as the ages of dikes. They are, of course, always newer than the rocks which they intersect; and where faults of different systems or directions intersect, the newer usually displaces the older. One of the models (**22**) shows this particularly well, the northwest-southeast fault being clearly newer than the northeast-southwest fault.

If the earth's surface were not subject to erosion, nearly



Shore-lines and fault-scarp at the base of the Wasatch Range, near Farmington, Utah.

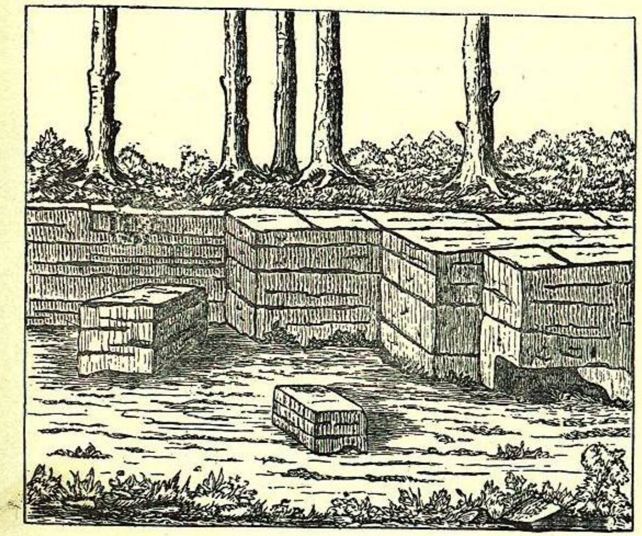
every fault of any magnitude would be marked on the surface by an escarpment equal in hight to the throw of the fault, as shown in several of the models (**21-22**); and, notwithstanding the powerful tendency of erosion to obliterate them, these escarpments are sometimes observed, although of diminished hight. Thus, according to Gilbert, the Zandia Mountains in New Mexico are due to a fault of 11,000 feet, leaving an escarpment still 7,000 feet high. The relief maps of the Henry Mountains in the west window show several such fault-scarps, and they are a prominent feature of the relief map of the Grand Cañon district in the south window. But, as a rule, there is no escarpment or marked inequality of the surface, faults, like folds, not being distinctly indicated in the topography. In all such cases we must conclude either that the faults were made a very long time ago, or that they have been formed with extreme slowness, so slowly that erosion has kept pace with the displacement, the escarpments being worn away as fast as formed. These and other considerations make it quite certain that extensive displacements are not produced suddenly, but either grow by a slow, creeping motion, or by small slips many times repeated at long intervals of time.

The relations of faults to erosion and their appearances on geological maps are farther illustrated by the wooden models, but the special features of each are explained on the labels, and need not be referred to here.

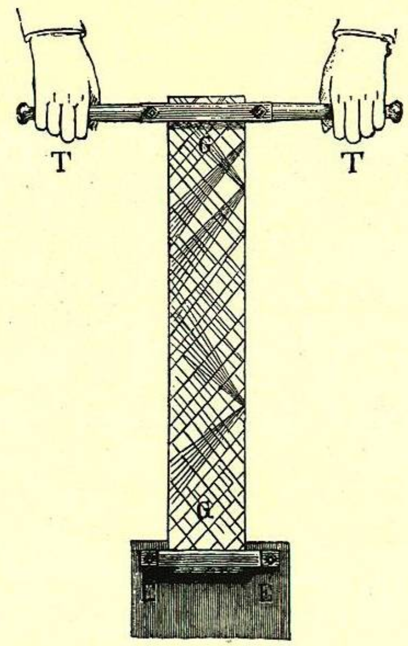
Joints and Joint-structure. — This is the most universal of all rock-structures, since all hard rocks and many imperfectly consolidated kinds, like clay (**3**), are jointed. Joints are cracks or planes of division which are usually approximately vertical and traverse the same mass of rock in several different directions. They are distinguished from stratification planes by being rarely horizontal, and from both stratification and cleavage planes by being actual cracks or fractures, and by dividing the rock into blocks instead of sheets or layers. The art of quarrying consists in removing these natural blocks; and most of the broad, flat surfaces of rock exposed in quarries, are the joint-planes (**4**). Some of the most familiar features of rock-scenery are also due to this structure,—cliffs, ravines, etc., being largely determined in form and direction by the principal systems of joints; and we have already seen that the same is true of veins, dikes, and faults.

Joints are divided by their characteristics and modes of origin into three classes as follows:—

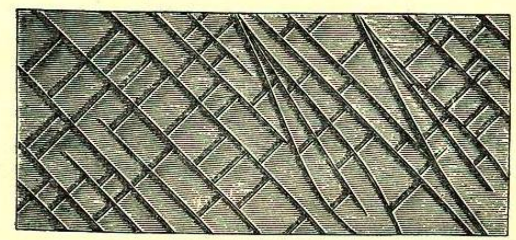
1. *The parallel and intersecting joints.* This is by far the most important class, and has its best development in stratified rocks, such as sandstone, slate, limestone, etc., and especially in the fine grained, brittle rocks. These joints are straight and continuous cracks which may often be traced for considerable distances on the surface. They usually run in several definite directions, being arranged in sets or systems by their parallelism. Thus, in the drawing (**4**) one set of joints is represented by the broad, flat surfaces in light, and a second set crossing the first nearly at right angles, by the narrower faces in shadow. One of the specimens on the second shelf (**21**) is an exceptionally good illustration of a single system of joints. Including the ends, it shows five even and closely parallel breaks or joint-planes. By the intersection of the different sets of joints the rock is divided into angular blocks, the forms of which depend upon the regularity, and angles of intersection of the joints. The more usual or normal forms of the joint-blocks are shown in the specimens, largely from the slate



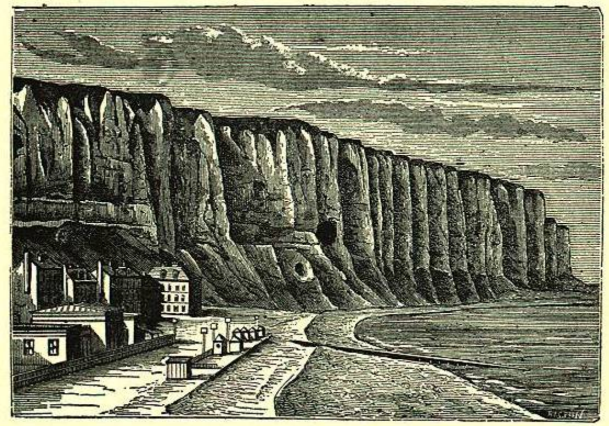
Parallel and intersecting joints in a quarry in the Forest of Fontainebleau.



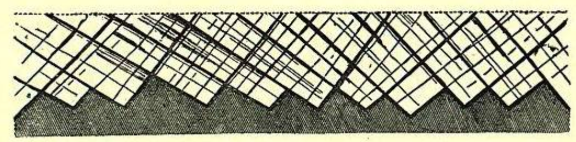
Apparatus for breaking plates of glass by torsion, with an example of the results produced.



Arrangement of fractures in a large plate of glass which was broken by torsion.



Sea-cliff 100 metres high at Tréport, France, showing the effect of joints which traverse the beds of chalk in two principal directions.



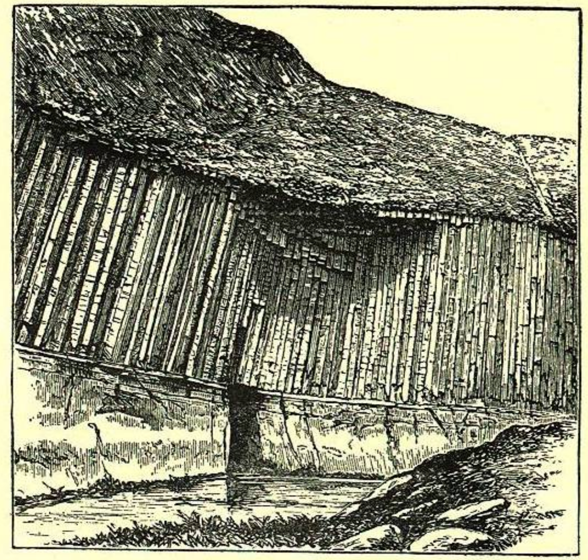
Plan of the joints in the cliff at Tréport, showing how they influence the process of erosion.

quarries of this vicinity, on the second shelf. Most of the blocks are bounded by two systems of joints and the bedding planes, the latter being horizontal, or forming the upper and under surfaces of the blocks as they are now placed. Occasionally the intersections of the joints are approximately rectangular, yielding cuboidal blocks (**22**), but more commonly they are oblique and the blocks are rhombic in form (**25, 27, 30**). In these cases the joints may or may not be oblique to the bedding planes. In one instance (**23**) the bedding surface is ripple-marked. Several of the blocks (**26, 28**) are bounded by joints of three different systems, and those bounded by four or five systems are not uncommon in the ledges. The two rhomboidal blocks of trap (**29, 32**) are interesting simply because the forms are unusually regular for rock of that character; and the jointing of the Roxbury pudding stone (**31**) is wonderfully regular and perfect, when we consider what a coarse, hard, uneven stone it really is. The two large blocks of slate on the third shelf (**41–42**) are intended especially to show how remarkably smooth and even the joint-faces sometimes are in rocks of that character.

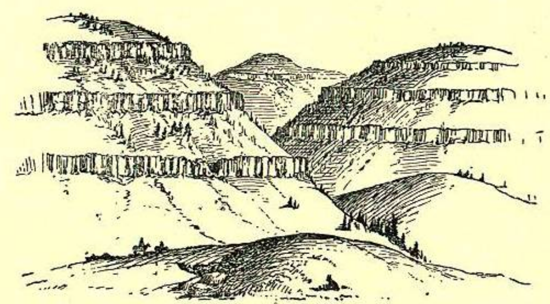
Joints not only facilitate mining and quarrying operations, but they also determine the size and character of the stones which a quarry can produce. Thus most of the slate around Boston is unsuited for building purposes, because it is too finely jointed. Material suitable for monolithic columns can, obviously, only be obtained where the joints are far apart in at least one direction. This condition is realized in miniature in the specimens of slate from Huit's Cove (**1**), the joint-blocks being distinctly prismatic in form. The long specimen on the back part of the second shelf (**34**) is rather exceptional in its dimensions. It was originally bounded by two parallel joint planes on the front and back edges, and by bedding planes above and below, but erosion has nearly effaced all of these. When the joints of one system are very close together the rock is sheeted and the jointing resembles stratification. The slab of granite from a quarry in Hingham (**68**) is an excellent illustration. This sheet-jointing is distinguished from that of the third class by not being horizontal. Joints are usually approximately plane, and the marked curvature seen in one of the specimens (**2**) is quite unusual. The jointed Miocene clay (**3**) is really semi-lithified; but joints are not uncommon in the plastic glacial clays of New England.

Although many explanations of this class of joints have been proposed, it has long been the general opinion of geologists that they are due to the contraction of the rocks, *i. e.*, that they are shrinkage cracks. We shall soon see, however, that they lack the most essential characters of cracks known to be due to shrinkage. More recently Daubrée has proposed to regard them as due to torsional strains, to the bending and twisting of the rocks; and this is undoubtedly a true explanation. The strains would, however, be developed too slowly to explain the remarkably regular fractures often observed, especially in rocks of coarse and irregular texture like the Roxbury pudding stone. To meet this difficulty, the present writer has advanced the view that the swift vibratory movements of the rocks known as earthquakes are an important if not principal cause of parallel joints. It is well known that earthquakes break the rocks; and it can easily be shown that the earthquake fractures must possess all the essential features of parallel and intersecting joints.

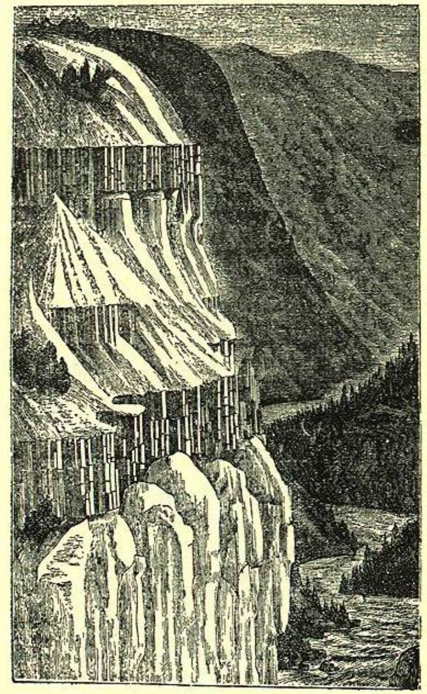
2. *The contraction joints or shrinkage cracks.* That many cracks in rocks are due to shrinkage, there can be no doubt. The shrinkage may result from the drying of sedimentary rocks; but more generally from the cooling



Columnar jointing of basalt in the vicinity of the Boat Cave, Island of Staffa.



Interbedded, columnar lava-flows near Saguache, Colorado.

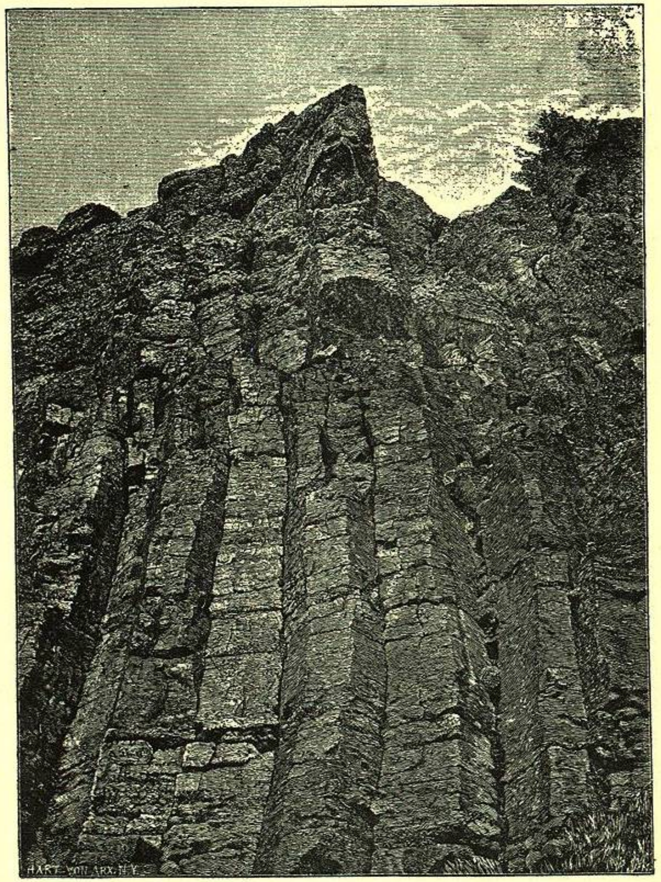


Columnar jointing in contemporaneous sheets of basalt, near the mouth of Tower Creek, Yellowstone National Park.

of eruptive rocks. Every one has noticed in warm weather the cracks in layers of mud or clay on the shore, or where pools of water have dried up (**65**) ; and we have already seen that these sun-cracks are often preserved in the hard rocks (**66**). The true shrinkage cracks have certain characteristic features by which they may be distinguished from the joints of the first class. They divide the clay into irregular, polygonal blocks, which often show a tendency to be hexagonal rather than quadrangular. The cracks are continually uniting and dividing, but are not parallel, and rarely cross each other. Sun-cracks never affect more than a few feet in thickness of clay, and are an insignificant structural feature of sedimentary rocks. In eruptive rocks, on the other hand, the contraction joints have a very extensive, and, in some cases, a very perfect development, culminating in the prismatic or columnar jointing of the basaltic rocks. This remarkable structure has long excited the interest of geologists, and, although the basalt columns were once regarded as crystals, and later as a species of concretionary structure, it is now generally recognized as the normal result of slow cooling in a homogeneous, brittle mass. The columns are normally hexagonal, and perpendicular to the cooling surface, being vertical in horizontal sheets and lava flows, as in the classic examples of the Giant's Causeway (**61**) and Fingal's Cave, and horizontal in vertical dikes (**67**). Vertical columns are sometimes called "palisades," as on the west bank of the Hudson above New York City; and "the devil's organ" is another common name. The columns begin to form on the cooling surface of the mass, and gradually extend toward the center, so that dikes sometimes show two independent sets of columns. This transverse prismatic or columnar jointing is imperfectly developed in many of the trap dikes about Boston; and at one point in Needham vertical columns are well developed in a surface flow of felsite. The small columns of basalt (**82**) are from the volcanic district of the Rhine, representing material that is extensively quarried for the manufacture of paving stones. The Giant's Causeway is represented by the model (**61**) and also by portions of two columns, one in the case (**81**) and one in the right window space. The columns are commonly divided at short intervals, as in these examples, by curving transverse fractures, which are attributed to the unequal cooling of the columns. The column of argillaceous limestone from the Delaware Water Gap, Pa., (**83**) represents a stratum in which prismatic jointing due, apparently, to shrinkage is well developed.

Shrinkage cracks in sedimentary deposits may be the result, in some cases, of volcanic heat instead of solar heat. Thus the columnar specimens of slate (**62**) and sandstone (**63–64**) on the fourth shelf are from the walls of dikes and might be classed among the contact phenomena. When the dikes were formed, the volcanic heat escaped from the trap into the sandstone and slate; and while the columnar structure was slowly developed in the trap by cooling, it was developed with almost equal regularity, but on a small scale, in the wall rocks, by heating and consequent desiccation, the columns being, in both cases, perpendicular to the walls.

3. *The concentric joints of granitic rocks.* In quarries of granite and other massive crystalline rocks, it is often



Columnar jointing in obsidian. Obsidian Cliff, Yellowstone National Park.

Pigeon Hill Quarry, Cape Ann, showing extreme development of horizontal jointing.

very noticeable that the rock is divided into more or less regular layers by cracks which are approximately parallel with the surface of the ground (**54**), some of the granite hills having thus a structure resembling that of an onion The layers are thin near the surface, become thicker and less distinct downward, and cannot usually be traced below a depth of fifty or sixty feet. These horizontal cracks are of great assistance in quarrying, and are now regarded as due to the expansion of the superficial portions of the granite under the influence of the solar heat. In reference to this view of their origin these may be called *expansion joints*.

Slickensides and Stylolites. These are minor phenomena related to joint-structure and illustrated by the specimens on the third shelf. Slickensides is the name given to the polished and striated surfaces often observed on joint-planes and on the walls of veins and dikes. This appearance is commonly explained as due to the friction when the rock surfaces were slipping over each other under great pressure ; and this mechanical theory is probably applicable where the slickensided surfaces are of the same nature as the mass of the rock, as in the case of the polished iron ore (**43**), coal (**48**), and quartz (**49**). In other cases, however, the slickensides exist only in a special mineral deposit on the rock surfaces, such as chlorite (**44**), epidote (**47**), iron oxide (**50**), and pyrite (**45**); and we may suppose that slipping occurred during the deposition of the minerals; although with chlorite (**44**), serpentine (**57**) and other hydrous species the mechanical explanation may be dispensed with and the slickensides referred to the swelling and consequent