easily seen in the large specimens which we have already noticed, and also in some of the others. In the block of slate (**24**) from Hull the parallel oblique lines mark the stratification; while the cleavage, which is somewhat indistinct, coincides with the flat surface on which the specimen rests. The adjoining specimen (**25**) from the great slate quarries of Slatington, Pa., is similar, except that the cleavage is more perfect. In the variety of roofing slates known as the ribbon slate (**42**) these darker bands marking the stratification can be seen crossing the cleavage surface at various angles.

A third important characteristic of cleavage, but one not so easily illustrated with specimens, is that it is usually associated with folded strata and very commonly with distorted or flattened fossils and nodules. The slaty pebbles in the cleaved conglomerate (**21**) have been flattened in the plane of cleavage.

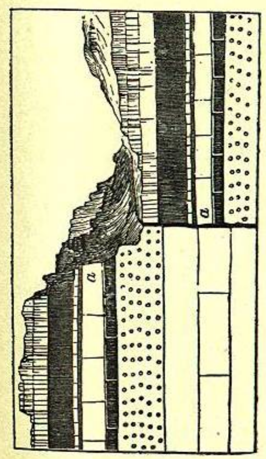
Many explanations of this interesting structure have been proposed, but that first advanced by Sharpe may be regarded as fully established. He said that *slaty cleavage is always due to powerful pressure at right* angles to the planes of cleavage. All the characteristics of cleavage noted above are in harmony with this theory. Cleavage is limited to fine-grained or soft rocks, because these alone can be modified internally by pressure, without rupture. Harder and more rigid rocks may be bent or broken, but they appear insusceptible of minute wrinkling or other change of structure affecting every particle of the mass. Since the cleavage-planes are normally vertical, the pressure, according to the theory, must be horizontal. That this horizontal pressure exists and is adequate in direction and amount, is proved by the folds and contortions of the cleaved strata; for the cleavage-planes coincide with the strike of the foldings, and are thus perpendicular to the pressure horizontally as well as vertically. The distortion of the fossils in cleaved slates is plainly due to pressure at right angles to the cleavage, for they are compressed or shortened in that direction, and extended or flattened out in the planes of cleavage. Again, Tyndall has shown that the magnetism of cleaved slate proves that it has been powerfully compressed perpendicularly to the cleavage. And, finally, repeated experiments by Sorby and others have proved that a very perfect cleavage may be developed in clay (unconsolidated slate) by compression, the planes of cleavage being at right angles to the line of pressure. When, however, Sharpe's theory had been thus fully demonstrated, the question as to *how* pressure produces cleavage still remained unanswered. Sorby held that clay contains foreign particles with unequal axes, such as mica-scales, etc., and that these are turned by the pressure so as to lie in parallel planes perpendicular to its line of action, thus producing easy splitting or cleavage in those planes. And he proved by experiments that a mixture of clay and mica-scales does behave in this way. But Tyndall showed that the cleavage is more perfect just in proportion as the clay is free from foreign particles, and in such a perfectly homogeneous substance as beeswax, he developed a more perfect cleavage than is possible in clay. His theory, which is now universally accepted, is that the clay itself is composed of grains which are flattened by pressure, the granular structure, with irregular fracture in all directions, changing to a scaly structure with very easy and plane fracture or splitting in one definite direction.

Observations on distorted nodules and fossils have shown that when slaty cleavage is developed, the rock is, on the average, reduced in the direction of the pressure to two fifths of its original extent, and correspondingly extended in the vertical direction. Thus, whether rocks yield to the horizontal pressure in the earth's crust, by folding and corrugation, or by the flattening of their constituent particles, they are alike shortened horizontally and extended vertically; and it is impossible to overestimate the importance of these facts in the formation of mountains.

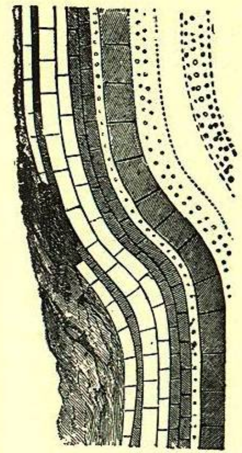
Faults or Displacements. — We may readily conceive that the forces which were adequate to elevate, corrugate, and even crush vast masses of solid rock were also sufficient to crack and break them; and since the fractures indicate that the strains have been applied unequally, it will be seen that unequal movements of the several parts must often result. If this unequal movement takes place, *i.e.*, if the rocks on opposite sides of a fracture of the earth's crust do not move together, but slip over each other, a *fault* (**41**) is produced. The two sides may move in opposite directions, or in the same direction but unequally, or one side may remain stationary while the other moves up or down. It is simply essential that the movement should be unequal in direction, or amount, or both; that there should be an actual slip, so that strata that were once continuous no longer correspond in position, but lie at different levels on opposite sides of the fracture. The difference in movement is known as the *throw*, *slip*, or *displacement* of the fault, and is commonly measured in the vertical direction.

Fault fractures rarely approach the horizontal direction, but are usually highly inclined or approximately vertical. When the fault is inclined to the vertical, the actual slipping in the plane of the fault exceeds the vertical throw, for the movement is then partly horizontal, the beds being pulled apart endwise. The inclination of faults, as of veins and dikes, should be measured from the vertical and called the *hade*. Faults are sometimes hundreds of miles in length; and the throw may vary from a fraction of an inch to thousands of feet.

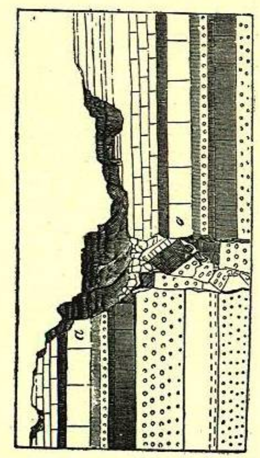
A transverse section, such as is shown in the specimen already referred to (**41**) and in most of the specimens and models, does not give the complete plan or idea of a fault; but this is seen more perfectly in the next specimen (**42**). In this little slab of slate we observe an obliquely transverse crack or rift not quite three inches long, and the layers of slate have been elevated on one side of this line and depressed on the other side, producing a fault having a maximum throw of one fourth of an inch. This is a small but very instructive example. We learn from it that a typical fault is a fracture or rift along which the strata have *sagged* or settled down unequally. The most important point to be observed here is that the strata do not drop bodily, but are merely bent, the throw being greatest at the middle of the fault and gradually diminishing toward the ends. In other words, every simple fault must, as in this instance, die out gradually; for we cannot conceive of a fault ending abruptly, except where it turns upon itself, so as to completely enclose a block of the strata, which may drop down bodily; but the fault is then really endless. The specimens on this shelf (third) are nearly all from Slate Island in Boston Harbor. This somewhat inaccessible islet, is probably the most favorable point in the Boston Basin for the study of some of the more important phases of faults; and the series of specimens will repay careful examination. Several of them (**46, 50**), besides the one al-



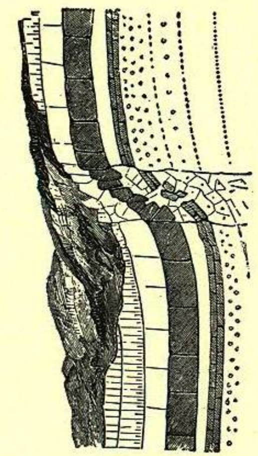
Section across a single fault.



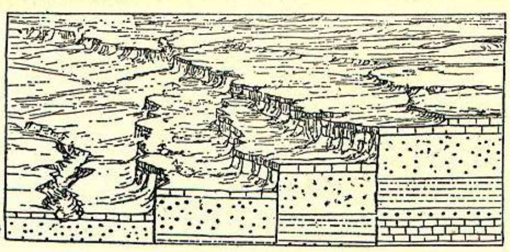
A monoclinal fold.



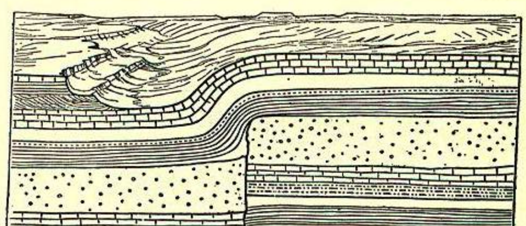
Section across a fault with walls widely separated, the intervening space filled with the broken strata.



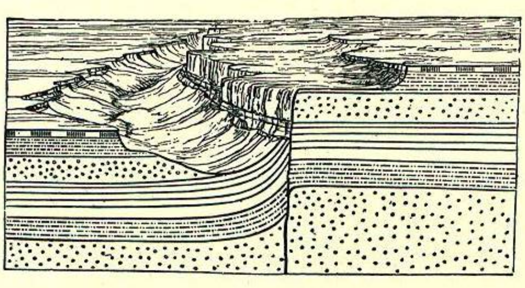
Section across a monocline which is passing, by crushing of the strata, into a fault.



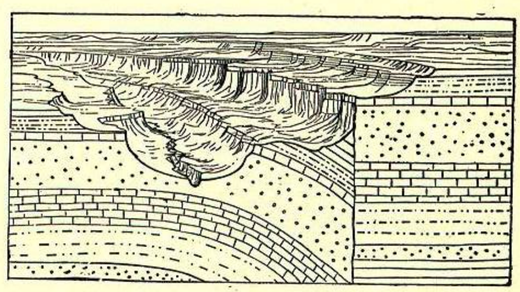
Section across a branching fault.



Fault and monocline.



Fault with thrown beds flexed upward—a dragged fault.



Fault with thrown beds flexed downward.

ready referred to, afford complete horizontal plans or views of typical faults. Where two or more faults appear in the same specimen, they are somewhat overlapping, exhibiting the step-like or *en echelon* arrangment characteristic of faults in general, as well as of various other structural features of rocks. In one instance of this kind (**50**) one of the faults was probably a foot or more in length when entire. But the most interesting of all these specimens is, doubtless, that one (**43**) in which the fault is cut off squarely and neatly midway of its length, thus combining the plan and section and giving a better idea of what a fault really is than pages of description.

The beautifully banded sandstones from the vicinity of the Hot Springs, in the Black Hills of South Dakota, (**62–65**) are also excellent illustrations, on a small scale, of various types of faulting. It will be most convenient, however, and save repetition, to present the different phases of faults systematically and refer to the specimens, so far as they are illustrative, in the same order.

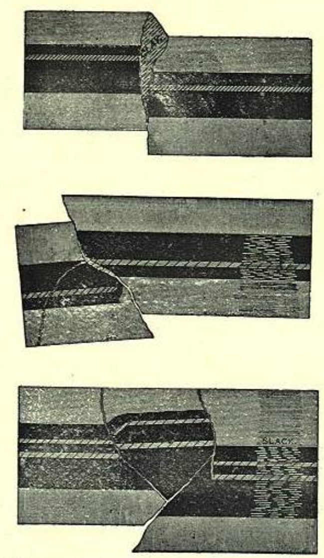
The rock above an inclined fault, vein, or dike is called the *hanging wall*, and that below the *foot wall*; and inclined faults are divided into two classes, according to the relative movements of the two walls. Usually, the hanging wall slips down and the foot wall slips up. Faults on this plan are so nearly the universal rule that they are called *normal* faults. They indicate that the strata were in a state of tension, for their broken ends are pulled apart horizontally, so that a vertical line may cross the plane of a stratum without touching it.

A few important faults have been observed, however, in which the foot-wall has fallen and the hanging-wall has risen.

These are known as *reversed* faults; and they indicate that the strata were in a state of lateral compression, the broken ends of the beds having been pushed horizontally past each other, so that a vertical line or shaft may intersect the same bed twice, as has been actually demonstrated in the case of some beds of coal.

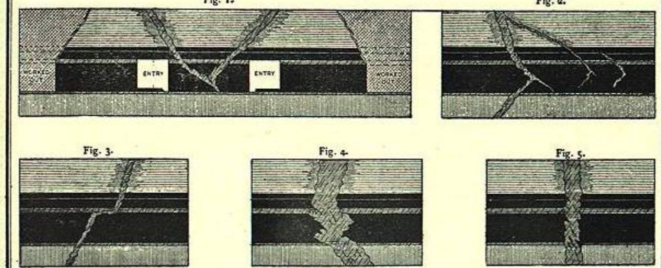
All of the models and nearly all the specimens show normal faults, the only clear exception being one of the Dakota specimens (**62**). This shows no fewer than five distinct and approximately parallel displacements, and in each case the hanging wall has risen relatively to the foot wall, the broken ends of the layers of sandstone overlapping. Obviously, this means horizontal compression and consequent slipping along a series of oblique fractures. The usual explanation of normal faults is that when the rocks are in a state of tension, a tendency exists to widen the fractures, and the hanging wall being thus left unsupported naturally drops down. The sufficiency of this explanation is especially obvious in the case of converging fractures, enclosing large, V-shaped blocks of strata. When these great wedges settle down the bounding fractures become normal faults. Several examples of these converging faults, which are also called trough-faults and compensating faults, are shown in the models (**2, 21**). Trough-faults, it may be added, are often limited in depth, since the displacement does not necessarily extend below the V-shaped block. A still better explanation, recently proposed by Professor Le Conte, introduces the principle of flotation and is illustrated by the blocks of wood on the back part of the second shelf (**24**). These blocks, it will be observed,

FORMS OF FAULTS



FORMS OF CLAY VEINS IN BITUMINOUS COAL BEDS.

Fig. 1. Fig. 2. Fig. 3. Fig. 4. Fig. 5.



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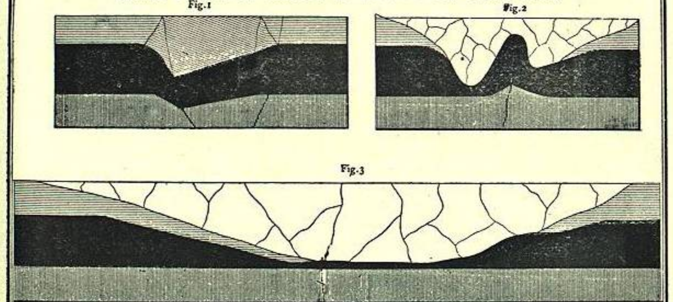
THREE FORMS OF FAULTS IN BITUMINOUS COAL BEDS.

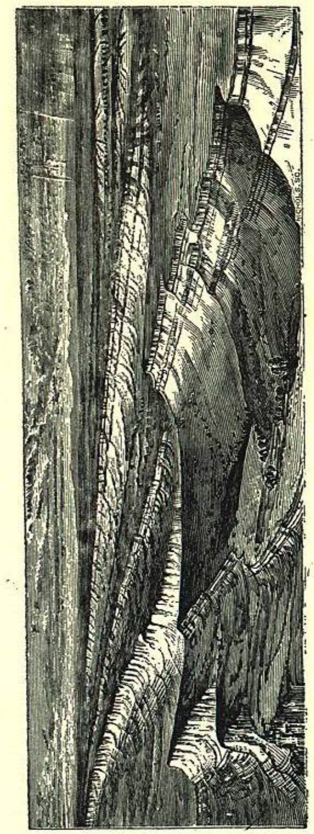
Fig. 1 Fig. 2 Fig. 3



were made by cutting a piece of plank obliquely the requisite number of times; and the plank thus divided may be compared to a portion of the earth's crust traversed by oblique fractures. Now imagine the blocks, all in their original positions, as floating on water and free to adjust themselves in obedience to the force of gravity. It is obvious that they will not retain their original horizontal positions, but each block will be tilted, and independently of the others, the over-hanging or heavy end settling down and the light end rising, until it gains the position of equilibrium shown in the present arrangement of the blocks, each block having been tested by floating it on water before placing it on the shelf. The point of special interest, of course, is that, after the principle of flotation has thus asserted itself, we find that each cut or plane of division in the plank has become a fault, and a normal fault, the hanging wall, in every instance, having risen and the foot wall settled down; and the earth's crust must, of course, tend to behave in a similar manner, if we, as the facts warrant, regard it as a layer divided by oblique fractures and resting upon a relatively mobile substratum or foundation.

Important reversed faults are believed to occur chiefly along the axes of overturned anticlines, where the strata have been broken by the unequal strains, and those on the upper side shoved bodily over those on the lower or inverted side; but, independently of this explanation, folds and faults are closely related phenomena. In the former the strata are disturbed and displaced by bending, in the latter by breaking and slipping; and the displacement which is at one point accomplished by a fold may, as the displacement increases or the rocks become more rigid, gradually change to a fracture and slip. This relation is especially noticeable with monoclinal folds, in which the tendency to break or shear the beds is often very marked. The large relief maps in the window cases of this room embrace clear examples on a large scale of closely related and connected faults and monoclines; and on a small scale we have the Slate Island faults on the second shelf, each one of which may be regarded as a modified monocline, the flexing having been sharp enough to overcome the cohesion of the slate at some points but not at others. In two of these specimens (**44**, **48**) there is no actual faulting, but the tendency to shear the slate is seen in the fact that it is pinched to about half its normal thickness along the axis of the fold. Again, in consequence of this pinching, the faults may die out vertically as well as horizontally. Thus, in another of the Slate Island specimens (**46**) the well-marked fault which we see on the upper surface is represented on the lower surface only by a faintly marked monocline.

Faults cutting inclined or folded strata are divided into two classes, according as they are approximately parallel with the direction of the dip or of the strike. The first are known as *transverse* or *dip* faults, and the second as *longitudinal* or *strike* faults. The chief interest of either class consists in their effect upon the outcrops of the faulted strata, after erosion has removed the escarpment produced by the dislocation. Dip faults cause a lateral shift or displacement of the outcrops, as is clearly shown by the north-south fault in the plaster model (**23**),

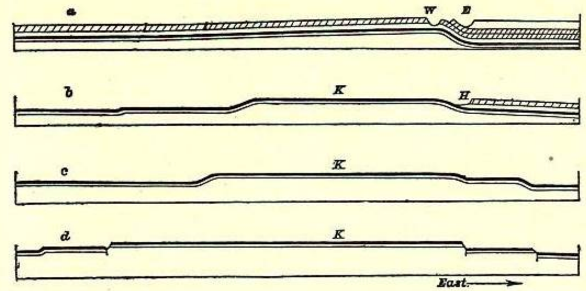


Bird's-eye view of cliffs of erosion thrown forward by a fault.

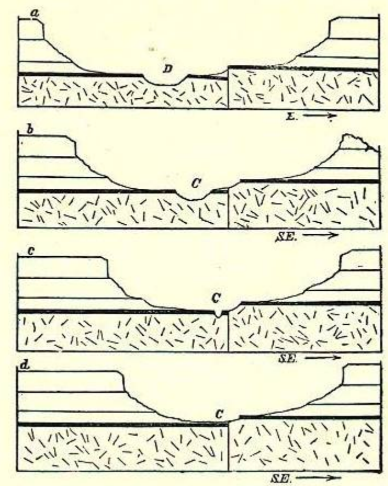
the fault being recognized in this case not only by the shifting of the bands of color marking the outcrops of successive strata, but also of the topographic features or ridges due to the unequal erosion of the strata. By reference to the direction of dip of the strata it is easily seen that the down throw side of this fault is on the right and the upthrow on the left. If the throw of the fault were reversed, the displacement of the outcrops would be reversed also. This model also shows a very clear strike fault. The effect of this fault is, evidently, to repeat the outcrops of the strata, the beds south of the fault being identical, as shown by the colors, with those north of it. This repetition of the strata in the same order proves the existence of a fault, as explained on the label, since repetition by folding is necessarily in the reverse order. Although strike faults thus commonly repeat the strata, and cause the apparent aggregate thickness of beds in the section to exceed the real thickness, they sometimes have the opposite effect, concealing a portion of the beds and making the apparent thickness less than the real thickness.

An extensive displacement of the strata is sometimes accomplished by a short slip along each of a series of parallel fractures, producing a step fault, as is so clearly shown in two of the Black Hills specimens (**62–63**), the fault being reversed in the first and normal in the second; and the normal series shows particularly well how a step faults simulates, in the general view, a monocline. Important faults are rarely simple, well-defined fractures; but, in consequence of the enormous friction, the rocks are usually more or less broken or crushed, sometimes for a breadth of many feet or yards. This feature, although especially characteristic of large faults, is well illustrated by one of the Black Hills specimens (**65**). This is crossed obliquely by a very distinct fault; and along either side of the fault the rock for a total breadth of about an inch is finely sheeted by numerous cracks approximately parallel with the main fracture. One result of this comminution is that fragments of the various beds are often strung along the fault in the opposite direction to the slipping, and this circumstance has been made use of in tracing the continuation of faulted beds of coal. In other cases the direction of the slip is plainly indicated by the bending of the broken ends of the strata, and the beds are sometimes turned up at a high angle or even overturned in this way. This is clearly shown in another of the Black Hills specimens (**64**), the layers along the very strongly marked oblique fault being flexed upward on the downthrow side; but, on account of the local bleaching of the colors, the downward flexing on the upthrow side can not be seen.

Since fault fractures are not usually plane, but undulating and often highly irregular, the walls will not coincide after slipping; and if the rocks are hard enough to resist the enormous pressure, the cavities or fissures produced in this way may remain open. Now faults are, in many cases, continuous fractures of the earth's crust, reaching down to unknown but very great depths and affording outlets for the heated subterranean waters; so that it is common to find a fault marked on the surface by a line of springs, and these are often thermal. The warm mineral waters on their way to the surface deposit part of the dissolved minerals in the irregular fissures along the fault, which are thus changed to mineral veins. This agrees



Parallel sections across a table-land, showing monoclines passing into faults.



Parallel sections across a valley of erosion which has, apparently, been determined by a fault.

with the fact that the walls of veins, as we have already seen, (page 232), usually show faulting, as well as crushed rock, slickensides, and other evidences of slipping.

The colored layers coinciding with some of the faults in the wooden model (**22**) are designed to represent mineral veins; still better, in several of the Slate Island specimens (**47, 49**) the fault fissures are occupied by veinlets of calcite,— small but exceedingly instructive examples. In one of these (**45**) the slate is much broken; and, although the calcite has been nearly all dissolved out, it may be regarded as, in plan at least, a miniature stockwork (page 241). The same general relations are observed, but less commonly, with dikes; and we have a superb illustration in the large specimen from Ontario (**81**). Crossing the bedded diorite are two nearly vertical dikes of granite, and along the right hand dike especially the diorite is distinctly faulted, the downthrow being on the left and nearly two inches, as shown by the feldspathic layers. The two specimens on the same shelf from Marblehead (**82–83**) are also very interesting in this connection. The first one is a mass of diorite traversed by a very regular dike of fine grained syenite; and this is sharply faulted twice by two later, oblique, and very slender dikes of the same material, the right hand slip being about two and a half inches in the plane of the fault. The second specimen, on the other hand, shows two parallel dikes of syenite in diorite broken nearly at right angles and slipped about two inches by a single prominent dike of syenite, the downthrow being on the left.