PERMANENT DISPLACEMENTS OF THE GROUNDS.

THE RESULTS OF THE SURVEYS.

Accurate surveys of a part of the region traversed by the fault-line of 1906 were made by the U. S. Coast and Geodetic Survey at various times. These have been grouped for the sake of discussion into three periods, namely: I, 1851–1865; II, 1874–1892; III, 1906–1907. These surveys, as discust by Messrs. Hayford and Baldwin (vol. I, pp. 114–145), show that in the intervals between the surveys certain definite displacements of the land took place. They bring out especially well the displacements which took place in the region north of San Francisco and the Farallon Islands during the time between the II and III surveys, an interval which included the earthquake of 1906. The field observations and the surveys were complementary; the former determined the relative displacements at the fault-line, and the latter the displacements at a

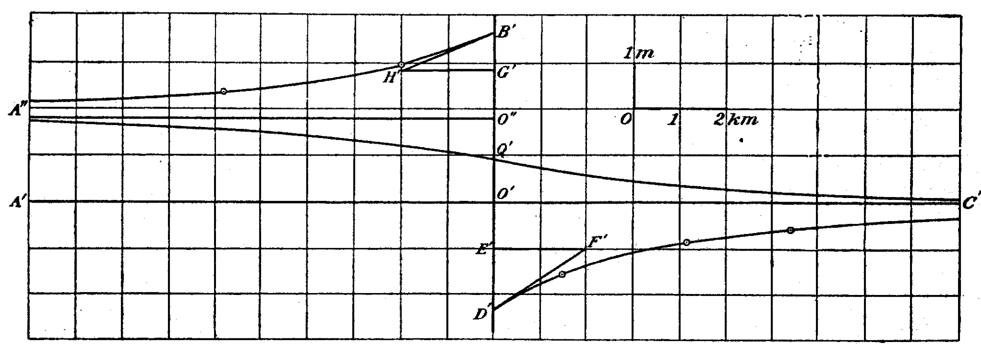

Fig. 5.

distance from it. The results of Messrs. Hayford and Baldwin may be exprest by fig. 5; they show that the displacements reached a maximum at the fault and were smaller as the distance from the fault was greater, in such a way, that a line which, at the time of the II survey, was straight, as $A'O'C'$, had, at the time of the III survey, been broken at the fault and curved into the form $A''B'$, $D'C'$. And, altho at a few points there is an indication of a compression or an extension at right angles to the fault, generally the movement was parallel with it. The figure is drawn to scale from the summary on page 133 (vol. I) and shows how the displacements diminish with the distance from the fault. The scale of displacements is 1,000 times that of distances; the curvature of the lines is so very small that it would be imperceptible if the two scales were the same.

The known length of the fault is about 435 km. (270 miles) and it is quite possible that it may be somewhat longer below the surface. Whatever may be its length, the fault terminates at some points beyond which no slip took place; the eastern side of the fault moved towards the southern region of rest and away from the northern region of rest; and the western side of the fault did just the opposite; there must have resulted near the northern end of the fault a compression of the land on the western side and an extension on the eastern; and near the southern end the extension must have been on the western side and the compression on the eastern side. There may have been a more or less irregular distribution of compressions and extensions along the course of the fault due to differences in the amount of the movement, but these, according to Dr. Hayford, are slight except in the region just south of San Francisco. The question arises: How were these compressions and extensions taken up? Did the volume remain constant and the density change; or did the density remain constant and the volume change; or did both changes occur? We have not sufficient evidence to answer this question; but the general properties of matter would indicate that both changes occurred. To the north of San Francisco Bay there seems to have been, in places, a very slight elevation of the land west of the fault, and the only satisfactory explanation so far offered of the action of the tide-gage at Fort Point (described in vol. I, pp. 367–371) indicates a small depression of the west side of the fault opposite the Golden Gate. It is not impossible, altho it is by no means clearly indicated, that the slight elevation of the western side along the northern part of the fault may be due to an increase in volume there, and that the probable depression opposite the Golden Gate may be due to a decrease in volume, which must have taken place in that region, on account of the smaller displacement just south of it.

Returning now to the curving of former straight lines at right angles to the fault as shown in fig. 5, the first analogy suggested by the lines is that of a bent beam. If a beam, which is long in proportion to its thickness, is supported at one end and a weight hung from the other, the beam bends into a curve very much like that shown in the figure; the under, concave surface is comprest; the upper, convex surface is stretcht; and between the two there is a neutral plane which is neither comprest nor stretcht. But when the thickness of the beam is great in comparison with its length, the distortion is due to the elastic shear of each layer over its neighbor. In this case the thickness of the beam would be 435 km. (270 miles) and the length probably less than one-twentieth as much; so that the distortion must have been due to shear and not to bending in the ordinary sense of the word.

THE NATURE OF THE FORCES ACTING.

We know that the displacements which took place near the fault-line occurred suddenly, and it is a matter of much interest to determine what was the origin of the forces which could act in this way. Gravity can not be invoked as the direct cause, for the movements were practically horizontal; the only other forces strong enough to bring about such sudden displacements are elastic forces. These forces could not have been brought into play suddenly and have set up an elastic distortion; but external forces must have produced an elastic strain in the region about the fault-line, and the stresses thus induced were the forces which caused the sudden displacements, or elastic rebounds, when the rupture occurred.[1] The only way in which the indicated strains could have been set up is by a relative displacement of the land on opposite sides of the fault and at some distance from it. This is shown by the northerly displacement of the Farallon Islands of 1.8 meters between the surveys of 1874–1892 and 1906–1907, but the surveys do not decide whether this displacement occurred suddenly at the time of the earthquake, or grew gradually in the interval between them; there are valid reasons, however, for accepting the latter alternative, as the following considerations show: The Farallon Islands are far beyond the limits of the elastic distortion revealed by the surveys, so that we can not ascribe their displacement to elastic rebound; and we have seen that this is the only kind of force which could have produced a sudden movement; and what

[1] We use the words *strain* and *stress* as they are used in the theory of elasticity. A *strain* is an elastic change of shape or of volume caused by external forces; and a *stress* is a resisting force which the body opposes to a strain, and with which it tends to diminish it.

is still more convincing, we shall shortly see that not only was the displacement of 1.8 meters of the Farallons between the survey of 1874–1892 and 1906–1907 insufficient to account for the slip on the fault, but the additional displacement of 1.4 meters which they experienced between the surveys of 1851–1865 and 1874–1892 leaves this quantity still too small.

We must therefore conclude that the strains were set up by a slow relative displacement of the land on opposite sides of the fault and practically parallel with it; and that these displacements extended to a considerable distance from the fault. Let us consider this process; suppose we start with an unstrained region, fig. 6, in which the line AOC is straight; suppose forces parallel to $B''D''$ to act on the regions on opposite sides of the line $B''D''$ so as to displace A and C to A'' and C''; the straight line AOC will be distorted

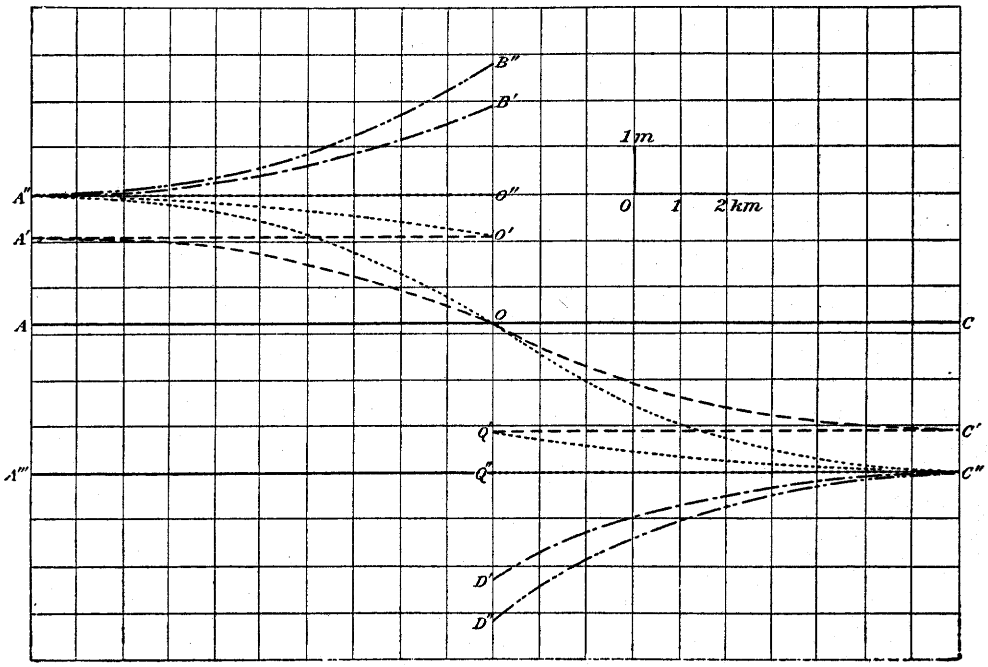

Fig. 6.

into the line $A''OC''$; if the distortion is beyond the strength of the rock, a rupture will occur along $B''D''$; the line $A''OC''$ will be broken and the two parts will become straight again and will take the positions $A''O''$ and $C''Q''$; and $O''Q''$ will represent the relative slip at the line of rupture, which will be equal to $A''A'''$, the sum of the opposite displacements which A and C gradually experienced when they were brought to A'' and C''. All points on the western face of the fault will move a distance OO'' to the north, and all points on the eastern face a distance OQ'' to the south. The straight line which occupied the positions $A''O''$ and $C''Q''$ just before the rupture will be distorted to $A''B''$ and $C''D''$, these lines being exactly like $A''O$ and $C''O$, but turned in opposite directions. The sum of $O''B''$ and $Q''D''$ will exactly equal $O''Q''$, the total slip.

When we examine the actual displacements about the fault-line, we find that the slip $B'D'$, fig. 5, about 6 meters, is fully 4 meters greater than the relative displacement of A' and C' since the survey of 1874–1892; this means that the region was not unstrained at that time, but that A' and C' had already suffered a relative displacement of about 4 meters from their unstrained positions; that is, two-thirds of the stress which caused the rupture had already accumulated 25 years ago. Going still further back to the surveys of 1851–1865, we find that the total relative displacement of distant points on opposite sides of the fault since that date amounts to about 3.2 meters, a little more than half enough to account for the slip on the fault-plane; therefore 50 years ago the elastic strain, which caused the rupture in 1906, had already accumulated to nearly half its final amount. It seems not improbable, therefore, that the strain was accumulating for 100 years, altho there is no satisfactory reason to suppose that it accumulated at a uniform rate.

We can picture to ourselves the displacements and the strains which the region has experienced as follows: let *AOC* (fig. 6) be a straight line at some early date when the region was unstrained. By 1874–1892, *A* had been moved to *A′* and *C* to *C′*, and *AOC* had been distorted into *A′OC′*; by the beginning of 1906, *A* had been further displaced to *A″* and *C* to *C‴*, the sum of the distances *AA″* and *CC‴* being about 6 meters; and *AOC* had been distorted into *A″OC‴*. When the rupture came, the opposite sides of the fault slipt about 6 meters past each other; *A″O* and *C‴O* straightened out to *A″O″* and *C‴Q″*; and the straight lines which occupied the positions *A″O″* and *C‴Q″* just before the rupture, were distorted afterward into the lines *A″B″* and *C‴D″*, these lines being exactly like the lines *A″O* and *C‴O* but turned in opposite directions. The straight lines, which occupied the positions *A′O′* and *C′Q′* in 1874–1892, were distorted into *A″O′* and *C‴Q′* in the beginning of 1906; at the time of the rupture their extremities on the fault-line had the same movements as other points on that line; *O′* moved to *B′* and *Q′* to *D′*. If we should move the left half of our figure so as to make *A′O′* continuous with *C′Q′*, fig. 6 would then be practically similar to fig. 5 and similar letters in the two figures would refer to the same points; in fig. 5, however, we have supposed *C′* to remain stationary and have attributed all the relative movement to *A′*, whereas in fig. 6 we have divided the movement equally between *A′* and *C′*; as we do not know the actual, but only the relative, movement this difference has no significance.

What was actually determined by the two surveys were the distances of points on the line *C′D′* and *A″B′* in fig. 5 measured from the line *C′A′*; and this is equivalent in fig. 6 to the distances of the line *C‴D′* from *C‴Q″*, and *A″B′* from *Q″A‴* less the distance *O′Q′*. The divergence of the lines *A″B′* and *C‴D′* from straight lines does not represent the strains which existed in the region just before the rupture, but only the strains accumulated before 1874–1892; we have seen that the total strains set up by 1906 are represented by the divergence from straight lines of the lines *A″O* and *C‴O*, or their counterparts, *A″B″* and *C‴D″*.

ILLUSTRATIVE EXPERIMENTS.

The following very simple experiments were made to illustrate the conclusions we have arrived at regarding the elastic strains and the relations between the slip at the fault-plane and the displacements of distant points. A sheet of stiff jelly about 2 cm. thick and 4 cm. wide was formed between two pieces of wood (fig. 7) to which it clung fairly well. A straight line *AC* was drawn on the jelly, which was then cut by a sharp knife along the line *tt′*; the left piece of wood was then moved about 1 cm. parallel with *tt′*, as shown in fig. 8; a slight pressure on the jelly prevented slipping along the cut line; the jelly was thus subjected to an even shear thruout and the original straight line *AC* was distorted into the line *A″C*; when the pressure on the jelly was removed, the elastic stresses set up by the distortion came into action, the two sides of the jelly slipt past each other along the line *tt′*, *A″O* straightened out to *A″O″*, and *CO* to *CQ″*, the slip *Q″O″* being equal to the distance *AA″*; and all the strain in the jelly was relieved. (The difference in the straight line *A″OC* in the jelly and the curved line *A″OC‴* (fig. 6) in the rock will be explained later.)

A second straight line *A″O″C″* was drawn across the jelly after *A* had been displaced, but before it was allowed to slip on the line *tt′*; when the slip took place, this line broke at O'' and took the position $A''B''$ and $C''D''$; the slip $D''B''$ equaled the displacement AA''; but the points A'' and C'', of course, remained unmoved.

A third experiment was made. A line $A'C'$ (fig. 9) was drawn after the jelly had been distorted, exactly as in the last experiment; the left piece of wood was then moved 0.5 cm. further and the line was distorted into $A''C'$; when the jelly slipt and resumed

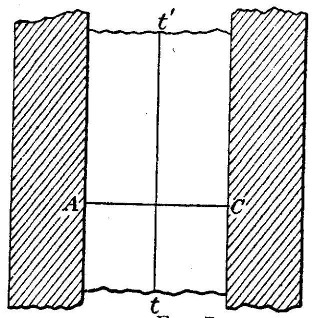

FIG. 7.

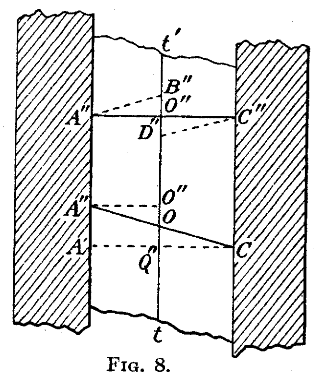

FIG. 8.

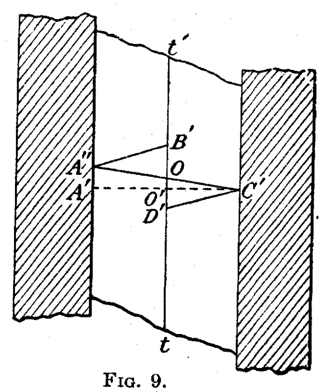

FIG. 9.

its unstrained position, the line $A''OC'$ broke into the two lines $A''B'$ and $C'D'$; the slip $D'B'$ was 1.5 cm., equal to the total displacement of the left piece of wood from its original position when the jelly was unstrained; and the distances of points on the line $A''B'$ near the fault, measured from the line $A'C'$, were about twice the distances from $A'C'$ of points on the line $C'D'$ at equal distances from tt'. But at a distance from tt' the displacements on the left were more than twice as great as those on the right; which agrees with the relative displacements actually observed (vol. I, p. 134). With the exception of the straightness of the lines the last experiment reproduces exactly the characteristic movements which took place at the time of the California earthquake. The letters in figs. 7, 8, and 9 correspond to those in figs. 5 and 6.

THE INTENSITY OF THE ELASTIC STRESSES.

The forces which caused the rupture at the fault-plane are measured by the distortion of the rock there, and if we can determine the angles which the lines $A''O$ and $C''O$ (fig. 6) make with AC at O, we can estimate these forces; these angles can be determined approximately from the analogous angles at B' and D'. Let us determine what the latter angles are. The lines $A''B'$ and $C''D'$ are constructed from Dr. Hayford's summary of the results of the surveys already mentioned and have the same curvature as the lines $A''B'$ and $C'D'$ in fig. 5; the data (vol. I, p. 133) may be collected in a table as follows:

TABLE 3. — *Displacements between II and III Surveys.*

No. of Points.	Average Distance from Fault.		Displacement between II and III Surveys.	
	East.	West.	South.	North.
	km.	*km.*	*m.*	*m.*
10	1.5	....	1.54	....
3	4.2	....	0.86	....
1	6.4	....	0.58	....
12	...	2.0	....	2.95
7	...	5.8	....	2.38
1	...	37.0	....	1.78

It will be observed that three points are determined on the eastern line near enough to the fault to enable us to draw the line fairly well and to extend it to the fault at D' (fig. 5). We have but two points determined on the western line near the fault, which are not enough to determine the character of the line; but a third point is determined from the fact that B' must be about 6 meters from D', and we can therefore draw the western line fairly well also. Its general form is like that of the eastern line, but its curvature is somewhat less. This is probably in part due to the fact that the rocks on the western side of the fault are more rigid than those on the eastern side; for former movements on this fault have raised the western side relatively to the eastern and brought the more rigid crystalline rocks nearer the surface.

In fig. 6 $B'B'' = O'O'' = 0.9$ meter, that is, half of 1.8 meters, the total relative displacement of A' and C' between the two surveys; and since $O''B''$ is a little less than half the total slip, on account of the greater rigidity of the western rocks, we may estimate it at 2.8 meters. Therefore $O''B'$equals 1.9 meters, and $O''B''$ is 1.47 times $O''B'$; and since the curves $A''B'$ and $A''B''$ are both curves of elastic distortion of the same substance the angle at B'' must be 1.47 times that at B'.[1] We can measure the angles at B' in fig. 5 and we find it 1/2,500; therefore the angle at B'' is 1/1,700; similarly we find the angle at D'' to be 1/1,000.

We can determine the force necessary to hold the two sides together before the rupture, which must exactly have equaled the stress which caused the break. The force per square centimeter is given by the expression ns where n is the coefficient of shear and s is the shear, measured by the angle at O or B'' for the western side of the fault, or the angle at O or D'' for the eastern side. We shall see further on that in the crystalline rocks below the surface the strain was somewhat greater than at the surface, so that we may assume that the angle corresponding to B'' lower down may be as high as 1/1,500.

The experiments of Messrs. Adams and Coker[2] give the value of n for granite as 2×10^{11} dynes per square centimeter (2,900,000 pounds per square inch); therefore the force necessary to produce the estimated distortion at the fault-plane at a short distance below the surface is 1/1,500 of this, or 1.33×10^{8} dynes per square centimeter (1,930 pounds per square inch). There are no very satisfactory determinations of the strength of granite under pure shear; tests made at the Watertown Arsenal[3] gave values ranging between about 1.2×10^{11} and 1.9×10^{11} dynes per square centimeter (between 1,700 and 2,900 pounds per square inch), but these values are apparently too small, for the specimens were subjected to tensions and compressions as well as to shear. The rock at a distance below the surface would probably have a greater resistance to shear on account of pressure upon it, and moreover it has not been subjected to the changes of temperature, etc., which the surface rocks experience, so that it probably has a strength greater than the higher figure given. We must therefore conclude that former ruptures of the fault-plane were by no means entirely healed, but that this plane was somewhat less strong than the surrounding rock and yielded to a smaller force than would have been necessary to break the solid rock. This idea is strongly supported by a comparison of the distance to which this shock and the earthquake of 1886, at Charleston, South Carolina, made themselves felt. With a fault-length of 435 km. (270 miles), the California earthquake was noticed at Winnemucca, Nevada, a distance of 550 km. (350 miles) at right angles to the fault; whereas the Charleston earthquake, with a fault-line certainly less than

[1] This reasoning is not perfectly rigid; the similarity of the lines $A''B'$ depends upon the similarity of strains set up during the intervals between the I and II, and the II and III surveys. These were probably fairly similar, as the difference between them represents the strain added between the II and III surveys which was only a fraction of the total strain at the time of the break; and the results obtained upon this assumption can not be very far wrong.

[2] An Investigation into the Elastic Constants of Rocks. Frank D. Adams and Ernest G. Coker, Carnegie Institution of Washington, Publication No. 46, 1906.

[3] Report of Tests of Metals, etc., made at the Watertown Arsenal, 1890, 1894, 1895. Washington, D.C.

40 km. (25 miles) long was felt slightly in Boston, a distance of 1,350 km. (850 miles). If we assume that the vibrations from the two disturbances had about the same periods and that a certain acceleration is necessary for a shock to be felt, we find that the amplitude of the vibration must have been about the same at Boston and at Winnemucca, for the two shocks, respectively; as the amplitude would diminish inversely as the distance for the Charleston earthquake, but much more slowly for the California earthquake on account of the length of the fault-line, the amplitude of the former disturbance must have been many times as great as that of the latter at the same distance from the origin; and the intensity must have been very many times greater per unit area of the fault-plane for the Charleston earthquake than for the California earthquake.

The above calculation of stresses applies especially to the region north of San Francisco; to the south the slip at the fault-line was, in places and perhaps for all this part of the fault, somewhat smaller. At Wright the slip on the fault-plane in the tunnel is given by the engineers as 5 feet, and the west side was shifted toward the north (vol. I, fig. 42, and pp. 111–113). This is a case of elastic rebound as at other parts of the fault. The character of the material in the tunnel and the numerous cracks in the surrounding mountain, one of which shows a relative shift opposite to that generally observed (p. 35), lead us to expect more or less irregularity in the distortion of the tunnel, which is confirmed by the figure. The greatest angle of shear must be something more than half the slip at the fault-plane divided by the distance over which the distortion is distributed; this gives 2.5/5,150 or 1/2,000, approximately. The angle of distortion is apparently slightly less here than further north. The smaller slip in the neighborhood of Colma, a little south of San Francisco, may be due to the partial relief of strain by the earthquake of 1868; for it shows that this region was under less strain at the time of the II survey than the region further north.

THE WORK DONE BY THE ELASTIC STRESSES.

We can also determine the work done at the time of the rupture; it is given by the product of the force per unit area of the fault-plane multiplied by the area of the plane and by half the slip. If we take the depth of the fault at 20 km. (12.5 miles), the length at 435 km. (270 miles), the average shift at 4 meters (13 feet), and the force at 1×10^8 dynes per square centimeter (1,450 pounds per square inch), we find for the work 1.75×10^{24} ergs (1.3×10^{17} foot-pounds), or 130,000,000,000,000,000 foot-pounds.[1] This energy was stored up in the rock as potential energy of elastic strain immediately before the rupture; when the rupture occurred, it was transformed into the kinetic energy of the moving mass, into heat and into energy of vibrations; the first was soon changed into the other two. When we consider the enormous amount of potential energy suddenly set free, we are not surprised, that, in spite of the large quantity of heat which must have been developt on the fault-plane, an amount was transformed into elastic vibrations large enough to accomplish the great damage resulting from the earthquake and to shake the whole world so that seismographs, almost at the antipodes, recorded the shock.

THE DISTRIBUTION OF THE DEFORMING FORCES.

In examining what forces could have caused the slow displacements which brought about the strains existing in the region before the rupture, we note that gravity does not seem to have been directly active, as the displacements were practically horizontal. Any force except gravity could only have been applied to a boundary of the region

[1] It is probable that the maximum strain was not produced at all parts of the fault-plane, and especially not near its ends; but when the rocks broke at one place, the stress was thrown upon adjacent parts and the fracture thus carried along; in this way the fault was probably made much longer than it would otherwise have been. This consideration leads us to put the maximum stress at three-quarters the value determined from the distortion of the rock.

moved. There is no direct evidence that forces brought into play by the general compression of the earth thru cooling or otherwise were involved, for there is no evidence that the surface of the earth was diminisht by the fault. It is true that the surveys did not extend over the whole length of the fault, and therefore are not decisive on this point, but so far as they went they show an extension of the region between San Francisco and Monterey Bay, between the surveys of 1851–1865 and 1906–1907.

A strong, shearing force would be produced along the fault-plane by forces making an angle in the neighborhood of 45° with it; that is, by either tensions or compressions in directions roughly north and south or east and west, or by a combination of the two. A tension alone could not have caused the rupture, for then the sides would have been pulled apart; an east-west compression would have brought Mount Diablo and the Farallon Islands nearer together and would have reversed the observed relative movements on opposite sides of the fault. The surveys, altho not entirely decisive, are against a north-south compression; and, moreover, the elastic distortion accompanying a compression which could produce a fracture 435 km. long would not have been restricted to a zone extending only 6 or 8 km. from the fault-plane. A shear exerted by forces parallel with the fault-plane on the eastern and western boundaries (which is equivalent to a north-south compression and an east-west tension at the boundaries) with no resistance at the under surface would have produced an even shearing strain thruout the region between them; and straight lines would have been changed into other straight lines, exactly as occurred in the experiments described above and illustrated in figs. 8 and 9. An additional compression or tension in any direction would not have altered this characteristic. Similar forces on the eastern and western boundaries with forces at the under surface resisting the movements would have produced some such distortion of the straight line AC into $A'C'$ as shown in fig. 10. The tendency to rupture would be greatest at A' and C' and least in the neighborhood of O; it is evident that such forces could not have produced a rupture at O, and the displacements are not like the displacements observed.

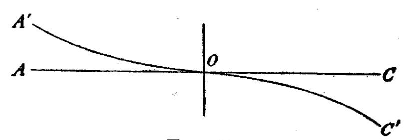

FIG. 10.

The only other boundary is the under surface of the moved region, and it is here that we must suppose the disturbing forces applied; and they must be distributed over this surface so as to produce the distortions observed.

NOTE. — Mr. Gilbert has suggested a modification of the experiments described above; instead of making the cut, which represents the fault, all the way thru the jelly, he suggested that it extend only a part way thru, and that it would thus more nearly represent the true conditions of the earthquake fault. This was tried, but the jelly was not strong enough to resist the forces developt during the displacement and the break was quickly extended all the way thru the jelly. It is not difficult, however, to see what forces would be developt under these circumstances. There are two cases: first, suppose there exists below the crust a region practically devoid of elasticity, in which only viscous forces can act, and suppose the fault extends to this region; we then come back to the last case considered. Second, suppose the elastic character of the rock extends well below the lower limit of the fault; such a case could easily exist if the strength of the rock increased with depth, even tho the strains continued far below the fault as great as they were within its limits. Let us consider the nature of the distortion produced in this case. We shall suppose the rock under elastic shearing strain, and when the rupture occurs, the shearing forces across the fault-plane, which upheld the strain, are annulled and the rock takes a new position of equilibrium under the new forces brought into action, in such a way that the surface line $A'OC'$ (fig. 11), straight just before the rupture, afterwards takes the position $A'O'$, $D'C'$. Below the limit of the fault no change takes place, but the original vertical plane thru $A'O'C'$ has been broken and warped, suffering no displacement below the fault, but gradually increasing its distortion until it corresponds to AO' and $D'C'$ at the surface.

An element of the surface a, on the eastern side of the fault, has been displaced to a' and a vertical line, $a''a$, thru a has been distorted into $a''a'$ by an elastic shear. The forces parallel with the fault acting on the element in its new position are: a shearing force to the southeast on its northeastern face, one to the northwest on its southwestern face, one to the northwest on its under surface due to the shear in the vertical plane; for equilibrium the sum of these must be zero, therefore the shearing force on the northeastern face must be greater than that on the southwestern; this relation holds for the whole length of the line $D'C'$; the shearing stresses therefore must become greater as we leave the fault-line. As the strains are proportional to the stresses, the curvature of the line $D'C'$ must become greater the further we go from the fault, until we reach the boundary where the forces are applied. This is true whether the forces are tangential forces applied along a boundary parallel with the fault, or a general north-south compression and an east-west tension. The surveys, however, on the east side of the fault, where alone they are sufficiently complete, show that the curvature of the distorted line was greatest near the fault-line; they could not, therefore, be due to a general compression and extension nor to simple tangential forces, but the distorting forces must diminish with distance from the fault-line; this could only hold if they were applied at the under surface, which brings us back to the conclusion already reached.

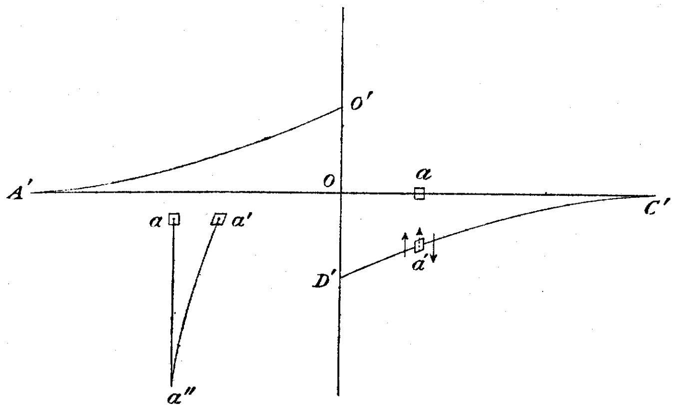

Fig. 11.

Let us suppose the straight line WOE in fig. 12 to represent a line at right angles to the fault in the unstrained condition; let this line be slowly distorted by the applied forces into the full line $WAOCE$ just before the rupture. We have heretofore only considered the region between A and C, that is, between Mount Diablo and the Farallon Islands, but we now extend our consideration to the whole region moved. It is evident that the displaced

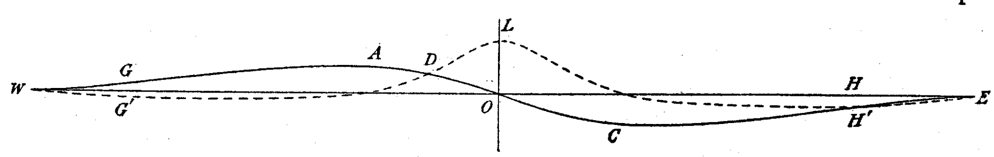

Fig. 12.

area must have some limit; the surveys only covered the region between A and C, and therefore throw no light on what occurred at greater distances from the fault. There is no reason whatever to believe that other ruptures and slips occurred outside the region between A and C; there is a gradual diminution of the intensity of the felt disturbance as the distance from the fault increases, with the exception of the Sacramento Valley, where the slight increase is entirely accounted for by the alluvial character of the ground, thus indicating that the whole disturbance originated in the one fault. The great intensity in the San Joaquin Valley may possibly be due to a local rupture; but this lies only opposite to the southern part of the great fault and does not affect the general argument, which is especially applicable to the region north of San Francisco. We conclude therefore that the displacement gradually dies out to the west of A and to the east of C, tho it may continue for a very great distance; and we assume that the line of displacement becomes asymptotic to the undisturbed line WOE at some distant points, W and E, which would be characteristic of any displacement gradually dying out. The shearing force at any point of this line is proportional to the shear, which equals the angle at that point which the line makes with its original unstrained direction. We have represented the value of this force by the broken line *WG′LH′E* in fig. 12. Starting at *W* where it is zero, the shearing force becomes negative; that is, it is directed in a southerly direction, reaching a negative maximum at *G′*, where the displacement curve has a point of inflection; it then diminishes in value, becoming zero at *A*, where the displacement curve is parallel with its original direction; it then increases rapidly in value, reaching a positive maximum, *L*, at *O*, the point of rupture; the shearing force to the east of the rupture has somewhat the same value it has at an equal distance to the west, tho symmetry is not required. The total shearing force which we have determined is not the force applied at each point under consideration, but is equal to the sum of all the forces applied to the east or west of the point; the actual force applied at each unit length of the line is proportional to the difference in value of the total shearing force at points a unit distance apart; that is, to the angle which the line representing the total shearing force makes with the line *WOE*; it is represented by *WGDOFHE* in fig. 13. Starting with a zero value at *W*, it first has a small negative value but becomes zero again at *G*; it then becomes positive and increases to a maximum at *D*, where the line of total sheer has a point of inflection—and dies down rapidly to zero at *O*, where the total shear is a maximum; it has somewhat similar but opposite values to the east of *O*.

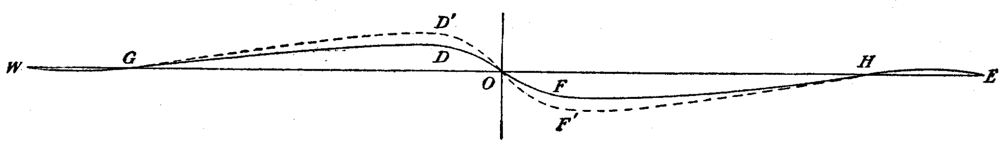

FIG. 13.

Without insisting on accuracy in small details the full line in fig. 13 shows in a general way the relative distribution of the forces, applied at the under side of the moved region, which brought about the California earthquake.

The distribution of the total shearing forces shows why in 1906 there was no break at the Haywards fault, where the break occurred which caused the earthquake of 1868. This fault is about 30 km. (18.5 miles) east of the San Andreas fault; and therefore in the neighborhood of *C* (fig. 12), where the surveys detected no displacement relative to Mount Diablo; in this region, as the figure shows, there was practically no shearing force, and therefore no break occurred. For the same reason there was no rupture at the San Bruno fault south of San Francisco. This fault is 4 km. (2.5 miles) east of the San Andreas fault and at that distance (fig. 5) the shearing force was only about one-third as strong as it was where the rupture actually occurred. We have seen that the elastic strain was probably accumulating for 100 years; it is quite possible, then, that the earthquake of 1868 partially relieved the strain for some distance south of San Francisco and that there would have been no fracture in this part of the San Andreas fault if additional strains had not been thrown on it by the rupture of the fault-plane further north.

It is to be noticed that the distances from *O* to *A* and from *O* to *C*, beyond which no distortion of the rocks occurred, were probably less than 10 km. (6 miles), and the distances *OG* and *OH*, over which the distorting forces were distributed, were probably ten or more times as great, and the total area over which they were applied was many times as great as the area of the fault-surface; the applied forces were therefore considerably smaller per unit area than the shearing forces at the fault; for the sum of all these forces on each side of the fault-plane must have equaled the shearing force at that plane plus the small shearing force at *G* or *H*, due to the slight reverse curving at this point.

As the dragging forces are applied at the base of the crust they have a moment about its center of gravity which is balanced by the moment due to stronger and greater shears near the bottom than near the top at the points *G*, *O*, and *H* (fig. 12); and lines at different distances below the surface which were straight and at right angles to the fault when the rock was unstrained became distorted in different degrees, the distortion from the surface downwards being somewhat as shown in fig. 14, where the three lines illustrate, in an exaggerated way, how the distortion of straight lines varies from the surface (1) to the bottom (3). Both the shearing strain and the strength of the rock increase with the depth, but the rate of neither is known; the depth at which the rupture first occurs is the depth at which the shearing strain becomes too great for the rock to withstand. It is pretty certain that this would not be very near the surface, and also that it would not be at the lowest part of the subsequent fault, but somewhere between those two points; for, wherever the rupture began, the strain must have been increased on all sides, the fracture must have been extended downwards as well as in other directions, until the strain was generally relieved. The determination, by time observations, of the origins of the earliest disturbance and of the beginning of the heavy shock place them between the surface and a depth of 40 km. (25 miles).

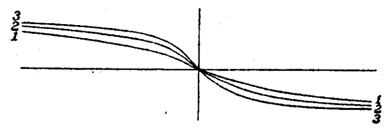

Fig. 14.

THE DISTRIBUTION OF THE SLOW DISPLACEMENTS.

We have no information regarding the absolute displacements of the land at a distance from the fault-line; we merely know that relative displacements occurred between the surveys of 1851–1865 and 1874–1892; and also between 1874–1892 and 1906–1907. We have for the sake of simplicity assumed that the regions at a distance from the fault and on opposite sides experienced nearly equal and opposite absolute displacements; but this is entirely unnecessary. It is possible, indeed probable, that the region on one side of the fault and at a short distance from it remained stationary, and that the slow displacements were all in one direction. The fact that the eastern side was above, and the western side below the sea-level, does not in the least indicate which side remained stationary; but the constancy in length and direction of the line from Mount Diablo to Mocho suggests that the eastern side was not displaced; for it seems improbable that, if this side had moved, the displacements would have been so nearly alike at the points mentioned that no change could be detected in the line joining them. Under this assumption our curve of displacements takes the form of the full line in fig. 15 instead of that in fig. 12. The curvature of this line between A and C is the same as in the former case; to the east of C the line is straight, and at some point to the west of A it again reaches its unstrained position. The total shearing force (represented by the broken line in fig. 15) has practically the same values as in the former case, except that it dies out near C; and the applied forces per unit area (full line in fig. 16) do not differ materially from the former case except that they do not extend farther east than C.

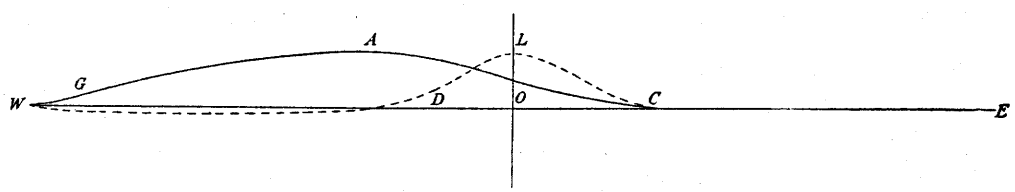

Fig. 15.

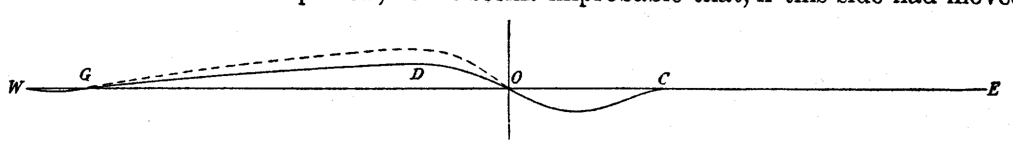

Fig. 16.

A POSSIBLE ORIGIN OF THE DEFORMING FORCES.

The reasoning so far has been strictly along dynamic lines and the results may be accepted with some confidence; but in attempting to find the origin of the forces which produced the deformation we have been studying, we pass into the region of speculation.

The theory of isostasy, which has been shown to be true on broad lines by geodetic observations, requires that there be flows of the material at some distance below the surface to readjust the equilibrium destroyed by the erosion and transportation of material at the surface. This suggests that flows below the surface may have been the origin of the forces we have been considering, for as Dr. Hayford has pointed out,[1] such flows would exert a drag on the material above them. The isostatic flows are the direct result of gravity and therefore easily understood, but no explanation has been found for the flows suggested as the origin of the forces in the case under consideration; nevertheless, as the forces must have been exerted at the lower surface of the moved region, it is worth while to determine the character of the flows which could have produced these forces, and leave to future observations the decision as to whether they really exist or not. Without assuming exact proportionality between the flow and the dragging force it exerts, we can say that the flow would be in the same directions as the force and would increase and decrease with it. Therefore the flow can be inferred from the diagram of forces in figs. 13 and 16. In the first case they consist of a flow to the north between G and O, and a flow to the south between O and H; they would not be uniform, but starting with a zero value at G and H, they would increase to maxima at D' and F', and decrease again to zero at O. The force between W and G, H and E, would not be due to flows but would be due to the resistance to the displacement of that part of the crust by the undisturbed material below; this displacement being due to the drag of the flows nearer the fault, transmitted elastically thru the crust to these regions; this is indicated by the reversed curvature of the line of displacements in fig. 12. The principle of continuity would naturally lead us to suppose that the flows were connected beyond the northern and southern ends of the fault; these portions of the flow would be so far apart and would have so short a length in comparison with the portions flowing north or south that their effects would be relatively insignificant. It may appear that there is a suggestion here of perpetual motion, but this is not so; all steady flows are in closed circuits, and it is only in case we should disregard the necessity of a proper supply of energy, that we should fall into the fallacy of perpetual motion.

The line of demarkation between the northerly and southerly flows need not necessarily lie exactly in the fault-line, but sufficiently near it for the growing shearing force to reach the limiting strength of the rocks at that point before it did at other points; nor is it necessary to suppose that the flows remain either constant in strength or in position; the contrary seems more probable; for if, as is natural to suppose, the forces which caused the earthquakes of 1868 and 1906 were of the same general character, the region of greatest shear, that is, the boundary between the flows, must have been in the neighborhood of the Haywards fault, about 30 km. (18.5 miles) further east, in 1868. Indeed, the displacements which occurred between the first two surveys indicate a somewhat different distribution of the flow from that suggested to explain the later displacements.

At first thought we might suppose that the movement of Mount Tamalpais in opposite directions relative to Mount Diablo in the two intervals between the surveys would indicate that it was on opposite sides of the boundary during these intervals respectively, but this would not necessarily follow. During the whole time that strains were being set up all points west of C moved to the north with respect to it; this relative movement in the second interval is represented on the eastern side of the fault by the distances between the lines $C''Q'$ and $C''Q''$ in fig. 6; and if we consider the curves in the figure as similar

[1] The Geodetic Evidence of Isostasy. John F. Hayford. Proc. Washington Acad. of Sci., 1896, vol. VII, pp. 25–40.

curves, it can be shown that these distances are a little less than four-tenths the observed distances between $C''D'$ and $C''Q''$, at equal distances from the fault. The observed southerly displacement of Mount Tamalpais between 1874–1892 and 1906–1907 was 0.58 meter; its northerly displacement between 1874–1892 and the beginning of 1906 must have been about 0.22 meter; and therefore its actual southerly movement at the time of the earthquake must have been 0.8 meter; and the opposite displacements of Mount Tamalpais in the two intervals would have occurred independently of the shifting of the underground flows.

If instead of considering the displacements roughly symmetrical and in opposite directions on opposite sides of the fault-line, we prefer to consider that they were all northerly, the conditions are represented in figs. 15 and 16; they are satisfied by the supposition of a single, northerly flow extending for some distance to the west, increasing to a maximum at *D* and diminishing rapidly to zero in the neighborhood of *O* (broken line in fig. 16). The southern force between *O* and *C* would be referred to the resistance which the underlying material would offer to the displacement of the crust above it.[1]

[1] Mr. Bailey Willis, on account of the forms of the mountain ranges bordering the Pacific Ocean, has concluded that the bed of the ocean is spreading and crowding against the land. He thinks in particular that there is a general sub-surface flow towards the north which would produce strains and earthquakes along the western coast of North America. Science, 1908, vol. XXVII, p. 695.