# SEISMOLOGICAL NOTES.

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## (a) Conditions Preceding and Leading to Tectonic Earthquakes.

There are two classes of earthquakes: Volcanic and Tectonic; the former, connected with volcanic outbursts, seem to be due to explosions or to the sudden liberation of steam; the latter are due to ruptures of the rock. It is only the latter class that we shall consider at present.

Rock, like all solids, is elastic, and when subjected to external forces it suffers an elastic strain; if this strain is too great for the strength of the rock to withstand a rupture occurs; but it is never possible for a rupture to take place until the rock has been deformed or stretched beyond its elastic limit. When the rupture occurs, the two sides spring apart under the elastic forces and come to positions of equilibrium, free of elastic strains. The following experiments have been made to illustrate these conditions. Two short pieces of wood were connected by a sheet of stiff jelly 1 cm. thick, 4 cm. wide and about 6 cm. long, as shown in Fig. 1. The jelly was cut through along the line, $tt'$, by a sharp knife and a straight line, $AC$, was drawn in ink on its surface. The left piece of wood was then shifted about 1 cm. in the direction of $t'$, and a gentle pressure was applied to prevent the jelly from slipping on the cut surface. The jelly was sheared elastically and the line took the position $AC$ shown in Fig. 2. On relieving the pressure so that the friction was no longer sufficient to keep the jelly strained, the two sides slipped along the surface $tt'$ and the line $AC$ broke into the two parts $AE$ and $DC$. At the time of the slip $A$ and $C$ remained stationary, and the amount of the slip, $DE$, equalled the shift which $A$ had originally experienced. A straight line, $A'C'$, was drawn on the jelly after the left side had been shifted, but before the jelly slipped along $tt'$. At the

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time of the slip, the same movement took place in the neighborhood of this line, as near *AC*, and *A′C′* was broken into two parts, *A′E′* and *D′C′*; the total slip, *D′E′*, being equal to *DE*. A third experiment was tried; the left piece of wood was shifted 1 cm. and a straight line was drawn across it; it was then shifted a half centimeter more and the straight line took the position *A″C″* in Fig. 3. When the jelly slipped along the surface, *tt′*, the line broke into the

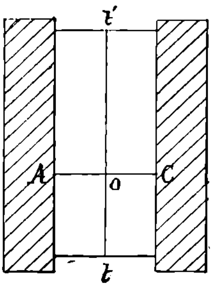


FIG. 1.

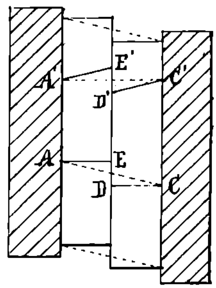


FIG. 2.

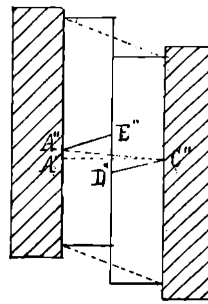


FIG. 3.

two parts, *A″E″* and *D″C″*; the slip, *D″E″*, being equal to the total displacement of the left side. Two characteristics of the movement are to be noted; the total slip on the ruptured surface equalled the total relative displacement of the blocks of wood; and, at the time of the slip the blocks remain stationary, and the whole movement at that time was an elastic rebound of the jelly to a condition of no strain.

These experiments illustrate as well as simple experiments could what occurred at the time of the California earthquake of April 18, 1906. Fortunately, early surveys had been made of this region which Dr. Hayford, in the report of the California Earthquake Commission has, for the sake of discussion, divided into two groups; I., the surveys made from 1851–65; II., those from 1874–92. A third survey (III.) was made after the earthquake in 1906–7. These surveys extended from Mt. Diablo, about 33 miles east of the fault, to Farallon Light House, about 22 miles west of it. They showed that between the I. and II. surveys Farallon Light House had shifted relatively to Mt. Diablo, 4.6 feet north-northwest, practically in a direction parallel with the fault-line; and between II. and III. surveys it had shifted 5.8 feet more in nearly the same direction, making a total shift in about 50 years of 10.4 feet.

Observations in the field on the offsets of fences and roads showed that at the time of the earthquake there was a relative movement of the two sides at the fault-surface, amounting to something like 20 feet, and it is only reasonable to suppose that this movement was equally divided between the opposite sides of the fault. The surveys show that the actual displacement which took place between II. and III. diminished as the distance from the fault became greater; on the east side the displacement practically died out at a distance of four or five miles from the fault, and on the west side the displacement became equal to that of Farallon Light House at about the same distance from the fault. All the phenomena were in close accord with the experiments described above. The main difference consists in the fact that a straight line on the earth's surface across the fault and at right angles to it did not break up into two straight lines, as in the experiment, but into two curved lines. We ascribe this curvature to the fact that the forces which produced the displacement of the ground were applied below the crust of the earth, whereas in the experiment they were applied at the outer boundary of the jelly.

The elastic rebound near the fault-surface, of course, took place suddenly at the time of the earthquake; and the surveys show that between I. and II., and between II. and III. there was a relative shift of very extensive regions on opposite sides of the fault, but the surveys do not determine whether these shifts took place suddenly at the times of the great earthquakes of 1868 and 1906, or whether they were the effect of a slow, gradual movement continuing through the years. We must turn to other considerations to decide this point. In the experiments we have described the elastic rebound was greatest at the ruptured surface, became progressively less at greater distances from this surface, and the jelly in contact with the wooden blocks did not partake of the movement at all. The experiments might have been varied and instead of a slow shift of the block gradually setting up an elastic shear, we might have set up the shear suddenly; but this was not necessary to produce the phenomena which we know took place at the time of the earthquake. It seems impossible to think that the general shift was sudden; for we cannot imagine what forces could have produced a sudden displacement, amounting to four or five feet, of a portion of the earth's surface covering thousands of square miles. But we have indubitable evidence, in the foldings of the rock common to all mountain chains, of the slow displacement of large regions to considerable distances; and unless such a displacement were slow enough to allow the rock everywhere to flow viscously and thus adjust itself to its new position, there would be places where the elastic stresses would from time to time be greater than the strength of the rock and ruptures would occur causing earthquakes.

This view of the case is so entirely in accord with the elastic properties of rock, and with the slow movements of large regions, familiar to geologists, that it commends itself strongly without further argument; but there is a consideration which seems almost decisive in its favor. In the experiments described we saw that the relative slip at the ruptured surface was exactly equal to the total relative shift of the wooden blocks; this, of course, was independent of the slow or sudden nature of the shift. The slip on the fault-surface at the time of the California earthquake was about 20 feet; therefore the shift of the more distant regions which brought about the break must have been as great; but the surveys show that between II. and III., the shift was only 5.8 feet, and between I. and II., 4.6 feet; that is, in all, only about 10.4 feet since the earliest surveys, some 50 years before the shock. We can therefore say, definitely, that the shift which set up the elastic strains which finally resulted in the earthquake, not only did not wholly take place at the time of the rupture but that even fifty years earlier it had already accumulated to about one half its final amount; that between the I. and II. surveys it increased to about three-quarters of this amount, and that the last quarter was added between the II. and III. surveys. It is hardly possible, in view of this history not to be convinced that the shift accumulated gradually.

Since the general order of events, that is, the setting up of elastic strains resulting in the rupture of the rocks which preceded and caused the California earthquake, were the consequences not of special conditions but of the general properties of rock, we may make the general statement that *tectonic earthquakes are caused by the gradual relative displacement of neighboring regions, which sets up elastic strains so great that the rock is ruptured; and that at the time of the rupture no displacements of large areas take place, but there occurs merely an elastic rebound, to an unstrained position, of the lips of the fault extending but a few miles on each side of it.*

It is not necessary of course that the slow displacement should set up a simple horizontal shear, as in the case of the California earthquake, but simply that an elastic strain of some kind should be produced by the relative displacement of adjoining regions. This may be due, for instance, to the slow sinking of a large region with the production of vertical elastic shears around its boundary, and when these shears become sufficiently strong a break will occur and the movement of the two lips will be vertical and in opposite directions, thus producing a fault-scarp. The main, sinking region, however, would not suddenly drop at the time of the break; there would only be an elastic rebound around its boundaries; its own displacement having taken place slowly over a long period of time. The elastic strains might also be set up by a horizontal compression, in which case the rock would be folded upward, and when the curvature became too great it would break like a bent stick, both sides of the broken surface flying upwards under the elastic forces and leaving an open fissure between them. Examples of this kind of rupture are only known on a small scale.

It is possible that the rupture may not be confined to a single surface, but may be distributed over a number of neighboring surfaces, and a small block between these surfaces may be displaced as a whole; but this must be looked upon as a minor phenomenon of the fault-zone, and is not an example of the readjustment of large blocks.

### (*b*) Some Characteristics of Seismological Instruments.

When efforts began to be made, some thirty or forty years ago, to produce an instrument that would record the actual movement of the ground caused by an earthquake, the object aimed at was to produce a "steady mass," that is, a heavy mass that would remain at rest in spite of the movement of its support; and by recording, either directly or through magnifying levers, its movement relative to the ground, the hope was entertained that the actual movement of the ground would be obtained. But the hope was futile. Every seismograph consists essentially of two parts: a heavy mass adjusted in a greater or less degree to a condition of neutral equilibrium, and the drum or other surface on which the record is made. If the mass could be adjusted absolutely to neutral equilibrium and could be kept in that condition in spite of the movement of its support, it would remain at rest, and would record the true movement of the earth; but the size of the recording apparatus is limited and in order that the record should be made on it, the heavy mass must remain pretty closely in one position, which is practically incompatible with neutral equilibrium. It was found necessary to keep the mass in stable equilibrium although the force brought into play by a small displacement might be very small. If displaced the mass would, therefore, vibrate about its position of equilibrium with a period of its own; and the record of every earthquake is the combination of the earth's movement with that of the heavy mass; and if the period of the vibrations of the earth happens to approach that of the heavy mass, the amplitude of the latter increases greatly, and indicates a movement of the earth much larger than actually occurs. We cannot deduce the movement of the earth from the record except by a careful analysis based on the mathematical theory of the seismograph. This, fortunately, has been worked out; but, unfortunately, it is rather complicated, and it is only in comparatively simple cases that it can be applied without very great labor.

The earlier investigators also thought that all solid friction or viscous damping reduced the sensitiveness of the instrument, and that a long period of vibration increased it. Solid friction is indeed always harmful and should be reduced as much as possible, but viscous damping is a great advantage and simplifies the interpretation of the record. Remembering that every earthquake consists of vibrations of many periods, a glance at figure 4 will show the great benefit of strong damping. The curves show the magnifying power of the seismograph so far as it depends upon the ratio of the period of the earth's vibration to that of the seismograph itself, and upon the viscous damping. The damping ratio is the ratio of the amplitude of successive swings of the heavy mass, when it is

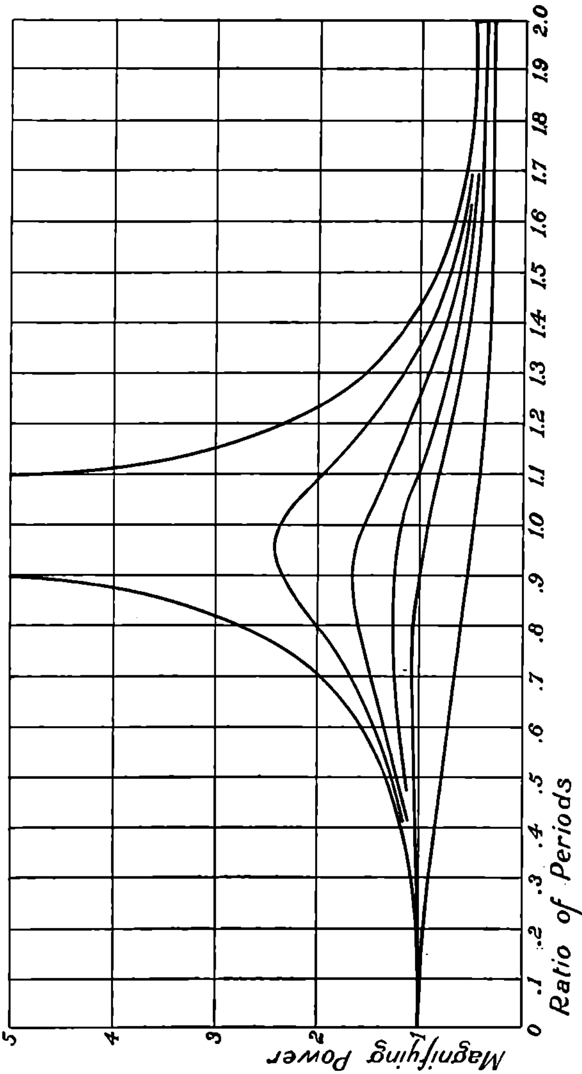


FIG. 4.

allowed to swing freely. If this ratio is nearly 1 : 1, that is, if there is very little damping and the amplitude of the swinging mass dies down very slowly, the curves show that the magnifying power for vibrations of very short period is unity; that is, the record gives the true amplitude of the earth's motion; for vibrations of longer period the magnifying power rapidly increases, and when the ratio of the periods is unity; that is, when the period of the earth's motion and the free period of the seismograph are equal, the magnifying power becomes extremely large. For still longer periods the magnifying power again decreases and when the period becomes very long, it becomes extremely small. Since, therefore, the vibrations of various periods are differently magnified, it is quite evident that the record of an earthquake would be greatly distorted, some vibrations being unduly emphasized, and others unduly minimized. It is just in this respect that damping is beneficial. Within limits, the inequality of magnifying power for various periods becomes less as the damping ratio becomes greater; and when the damping is great enough to reduce the relative amplitude of successive swings in the ratio of 8:1, the magnifying power is nearly uniform for all periods less than that of the seismograph. A seismograph, damped to this amount, and with a period as long as the longest of those present in the earth's vibrations, would give a much truer representation of the earth's movement.

The advantage of a long free period is not to increase the sensitiveness of the seismograph but to increase the range of periods over which its sensitiveness may be maintained. Contrary to a very general belief, the magnifying power for vibrations of very short periods is not affected by the amount of damping.

### (*c*) Suggestions for a National Seismological Bureau.

The work of collecting information regarding earthquakes, and studying this material is so extensive that it cannot be carried out thoroughly except with the aid of the federal government. The United States is almost the only country of importance which does not give governmental aid to the study of earthquakes; and, although, fortunately, the larger part of this country is only subject to occasional slight shocks, extremely destructive shocks have occurred within our boundaries, and certain districts are frequently visited by earthquakes which cause much damage. The study of earthquakes is a thoroughly practical subject, and if properly prosecuted, will be of distinct benefit to the country.

Let us glance, for a moment, at the special problems which a national bureau should take up. They may be enumerated as follows:

1. The collection of information regarding earthquakes in the United States and its possessions.

2. The study of the distribution of earthquakes in the United States and the preparation of maps showing this distribution and its relation to the geological structure.

3. The study of special regions, such as the California coast.

4. The prompt examination of a region which has suffered a severe earthquake.

5. The collection of information regarding earthquakes under the sea, and tidal waves.

6. The study of the earthquakes of the Gulf of Mexico and the Caribbean Sea from the records of instruments around these areas.

7. The issue of monthly bulletins, giving the records of felt earthquakes and of seismographs in the United States.

8. The study and dissemination of information regarding the best methods of construction in areas subject to earthquakes.

9. The theoretical study of earthquake instruments.

10. Other theoretical studies.

The variety of these studies requires the sympathetic cooperation of many branches of the government for their successful prosecution. The Weather Bureau and the Post Office Department are especially adapted to collect information regarding felt earthquakes; and the trained observers of the former, distributed as they are all over the country, could readily add a seismograph to the instruments under their charge and obtain important records of distant and near earthquakes. The Navy, through its personnel and through its Hydrographic Office has especial facilities for collecting information regarding earthquakes felt at sea. The Geological Survey alone could study the relation of geological structure to the occurrence of earthquakes; and the Coast and Geodetic Survey has on its staff able mathematicians capable of deducing the characteristics of the interior of the earth from the velocity of earthquake waves through it, and of finding the answer to the question whether earthquakes produce changes in the earth's magnetism.

In looking over the history of the various scientific bureaus of the government, we see that they were, in general, started by the Smithsonian Institution, and after their work had been thoroughly marked out and justified, they became independent. It seems not only conservative, but most practical, to follow this precedent in the establishment of a seismological bureau; for the Smithsonian is excellently adapted for prosecuting earthquake studies, and it could probably secure the hearty cooperation of all the other departments of the government more easily than could any single one of these departments.