13. *An* Earthquake Model. By John William Evans, D.Sc., LL.B., F.G.S. (Read June 15th, 1910.)

Some eighteen months ago, Mr. R. D. Oldham showed to this Society a model designed to explain the mechanism of the earth-movements at the time of the Californian earthquake of 1906 in the neighbourhood of the San Andreas Fault.[1] Though of great value in assisting us to realize the nature of the changes which then took place, it does not give prominence to the time-element so as to indicate the succession of events that led up to the earthquake shock; and it is to illustrate this aspect of the question that I have had the model constructed which forms the subject of the present paper.

It will be convenient for me, in the first place, to describe succinctly, from my own standpoint, the stages into which the conditions that precede an earthquake may be divided.

I shall on the present occasion put on one side earthquakes which are in the nature of landslips, as well as those which are the immediate result of the explosive action of the gases in igneous magmas, although there are authors who attribute to both of these modes of origin a greater importance and a more frequent occurrence than is usually accorded to them.

The typical earthquake, then, including great earthquakes like that of 1906, is, in my belief, the ultimate result of the slow relative movement of great masses of the earth's crust extending in most cases far beyond the area immediately affected by the shock. This differential creep may be in a horizontal, or in a vertical, or in any intermediate direction. As it proceeds, the intervening tract is subjected to stresses resulting in distortion or strain, so that a transverse line which was originally straight becomes curved. When the stress exceeds anywhere the limit of strength of the rocks, fracture will occur. This will relieve the stress, and if the adjoining portions of the rock have not lost their original elasticity through long subjection to the stress, they will swing back and resume their former relation to the mass with which they still remain connected.[2]

This motion of release appears to be identical with the molar displacement or 'mochleusis' of Mr. Oldham. It will obviously be greatest near the fault (except so far as it is affected by friction between the moving portions of the rock on opposite sides), and gradually diminish, as was the case in the earthquake above mentioned, as the distance from the fault increases.

Under the accelerating force of the elasticity of the rock the

[1] Quart. Journ. Geol. Soc. vol. lxv (1909) p. 1.

[2] I have assumed in my descriptions that there is only one fracture, and that the movements are everywhere parallel to it. In practice there will in most cases be smaller secondary fractures, especially near the surface, each with its local movements of release. The great length of the San Andreas Fault shows, however, that it is not of this secondary character.

movement will proceed with increasing velocity, until it meets with an obstacle or the position of equilibrium is passed. In the former case it will be brought to a standstill with a sudden jar made up of numerous short-period vibrations. In the latter it will either continue with diminishing velocity, until it is arrested by an obstacle in the manner already described; or, what is probably a rare occurrence, the swing will be prolonged until the accumulation of negative acceleration due to the elasticity of the rock exactly cancels the velocity at the position of equilibrium. In either event it will return to this position, about which it will swing to and fro until it comes to rest under the influence of friction, which will of course profoundly affect all the movements that have been described.

It is, I believe, the short-period vibrations due to the sudden check of the fault-movement when an obstacle is encountered, which constitute the earthquake properly so called, and are the cause of its destructive action. The fracture which initiates the movement doubtless gives rise to minor vibrations, and the same is the case with the friction between the rocks as they brush past each other. To the latter action must also be attributed the grating or rumbling sounds which are often described as heralding a violent shock.

There still remains to be considered the question of the long-period vibrations which form the more important portion of the records of distant earthquakes, and are separated from the shorter vibrations that precede them by their inability to traverse the highly-compressed deeper portions of the earth's interior. They may very well be attributed to the backward and forward swing of the severed rocks about their position of equilibrium, although it is possible that in some cases they may represent beats due to the interference of vibrations of shorter period.

The strength of the earthquake will evidently depend largely on the degree in which the rock has retained its elasticity. If the creep be very slow, the rock may be able to adjust itself to the new conditions, and there will be no fracture and no shock. A similar result may ensue, if the rocks are at a high temperature or under great pressure. If, on the other hand, they are more or less incoherent, they will possess no elasticity, and fracture may occur without a shock ensuing. In the same manner movement may occur without shock along a pre-existing fault, the sides of which do not adhere to each other. In these cases, however, the movement will probably be of the same slow character as that of the main rock-masses on each side of the fault.

The model which I have designed to illustrate these principles has been constructed by my cousin, Mr. Frederic J. Bakewell, electrical and mechanical engineer, to whom I am much indebted for his ingenuity and resource in overcoming the difficulties that presented themselves.

It consists of two vertical rectangular frames (f_1 & f_2 in the photographs—figs. 1, 2, & 3, p. 348) mounted side by side on a common

Fig. 1.—*Original configuration, before slow relative movement.*

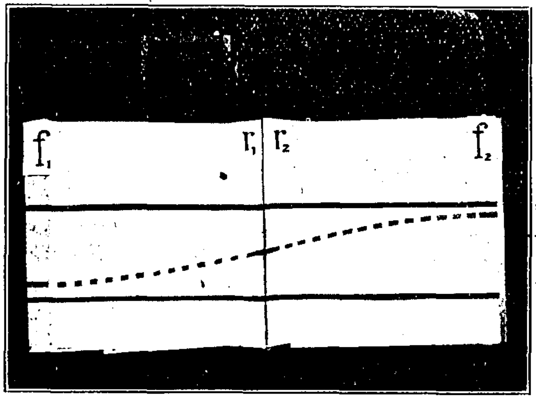
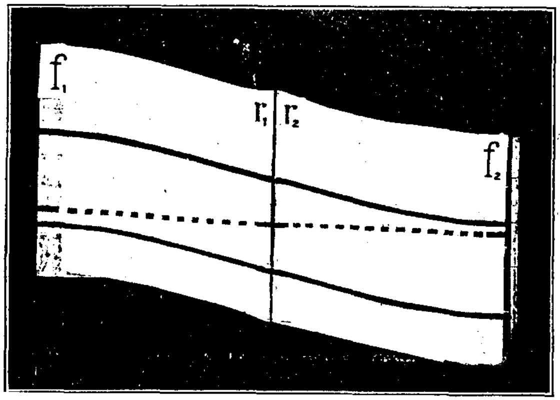
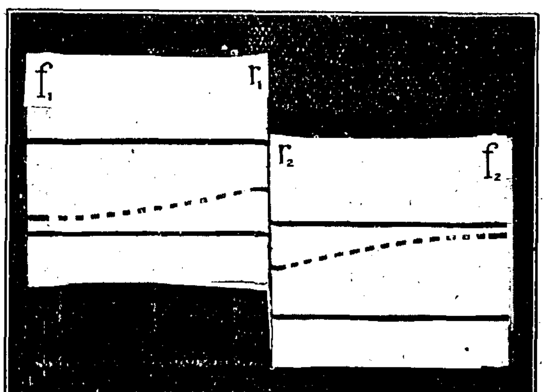


Fig. 2.—*Configuration after slow relative movement, immediately before fracture and earthquake.*



[The interrupted line is now supposed to be drawn as a straight line.]

Fig. 3.—*Configuration after earthquake.*



support. That on the left (f_1) is capable of being moved upwards[1] by the action of a screw. The other on the right (f_2) can move a short distance to the left. To each of these frames a number of steel strips are attached at one end. These are covered with a thin flexible silk membrane, which shares their movements. The free ends of the steel strips attached to each frame are pivoted in a movable vertical rod. The two rods r_1, r_2, one for each frame, are at first closely connected by an interlacing loop of string, so that a continuous surface is obtained which comprises both membranes, as shown in fig. 1 (p. 348). It represents the whole region before the commencement of the creep. It is seen to be traversed by continuous horizontal straight lines as well as by an interrupted curved line, the meaning of which will appear immediately.

The screw is now turned so that the frame f_1 moves upwards into the position shown in fig. 2, when the lines which were formerly straight and horizontal become curved in a sigmoid manner, the curvature being reversed where they traverse the vertical rods. This position represents the conditions after the slow creep has progressed until the limit of the strength of the rocks has been just reached, so that fracture is on the point of taking place. The interrupted line now stretches straight across, horizontally, from side to side. It may represent straight roads or fences transverse to the fault made in the period immediately preceding the earthquake.

The 'fracture' is effected by cutting the string. This releases the two rods, which at once fly apart, r_1 upwards and r_2 downwards. Shortly after they have passed the position of equilibrium they are brought to a stop by the collision of two metallic masses attached to them, which are thrown into rapid vibration and sound the corresponding notes. As they are not quite in unison, distinct beats are heard. At the same time, the rods swing back and vibrate with a comparatively slow period about the position of equilibrium. The model finally comes to rest in the position shown in fig. 3, where the interrupted line which was straight in fig. 2 has become curved in fig. 3, resembling very closely the lines drawn as a result of the geodetic observations taken since the Californian earthquake.[2] At the same time, the ends of the lines are seen to be turned back by the friction between the two sides of the fissure.

If the model is to be considered as a representation of the course of events in connexion with the Californian earthquake, the slow motion of the left-hand frame expresses a gradual creep of the bed of the Pacific to the north-west relatively to the North American continent, giving rise to a region of strain in the neighbourhood of the coast-line, which increases until fracture occurs in the San Andreas Fault.

[1] Namely, upwards in the photograph. The model works best, however, when the frames are horizontal.

[2] R. D. Oldham, Quart. Journ. Geol. Soc. vol. lxv (1909) fig. 2, p. 4.

Such a movement may be explained without difficulty, on the hypothesis that the earth as a whole is subject to powerful tangential compression. This view has, it is true, been called in question, on the ground that contraction of the earth's interior due to cooling is insufficient to account for the folding and overthrusts which can be shown to have taken place. It must be remembered, however, that the interior must also diminish in volume as a result of volcanic eruptions and loss of water and other materials from springs of intra-telluric origin. At the same time, the crust is always expanding in consequence of the gradual hydration of its crystalline rocks, which probably constitute by far the greater portion of its mass, by water both of intra-telluric and of atmospheric origin.[1] Not only does this take place in the great tracts of the fundamental gneiss, but every intrusive boss or dyke must exercise expansive action as its alteration proceeds.[2]

The Pacific coast of North America constitutes a line of weakness connected with the folding that gave rise to the coastal ranges. In the extreme north of the Pacific, in the neighbourhood of the Aleutian Islands, this changes from a south-east and north-west to an east-and-west direction. In North America, on the other hand, there is no transverse—that is to say, east-and-west—line of weakness in the north, but to the southward we have one stretching through the Antilles and Mexico. Similar relations prevail on the Asiatic side. Accordingly, as the crust adjusts itself by folding and thrusts where it is weakest, a northward movement of the bed of the North Pacific relatively to both North America and Asia may be expected to take place. This is, in fact, what occurs, for a relative movement to the north can be shown to have taken place not only on the west side of the great Californian fault in 1906, but also on the east side of the well-known Neotale fault in Japan at the time of the great earthquake of 1891.

This gradual northward movement of the North Pacific relatively to the continents on either side must be accompanied by intense folding and thrusting in the neighbourhood of the Aleutian Islands; and immediately to the south of these is one of the most active earthquake-tracts of which we have any knowledge. At the same time, the lines of weakness on the borders of the continents must be affected to some extent in a similar manner. It is true that in the case of the earthquake of 1906 the movement was mainly longitudinal parallel to the coast, but there were not wanting indications of a certain amount of overthrusting of the continental over the marine area.

[1] It is probable that pneumatolytic action in general usually causes expansion: for instance, in the conversion of a granite into a greisen.

[2] I need not say that there are other causes, such as tidal action and changes in rock-temperature, which may in places be responsible for variations of tangential pressure or the local occurrence of conditions of tension, and the latter undoubtedly also appear in the course of the development of great flexures in the earth's crust.

I have not attempted in the model to illustrate movement of more than one description at the same time. The same model may, however, be employed to illustrate an earthquake connected with a fault in which the vertical movement is the more important, whether it be an incident of the folding due to the compression of the earth's crust, or of the rise of mountain-ranges as a result of the removal of material from their summits and slopes and its accumulation on the adjoining plains or sea-bed.

We are told that, after the earthquake of 1822, the shore-line of Chile was found to be raised. This probably represents a rise by its own elasticity of the tract under strain on the landward side of the fault when released by fracture. The temporary withdrawal of the sea, which so often accompanies an earthquake on that coast, has been attributed to a depression of the sea-bottom. This may represent the corresponding movement in the contrary direction on the other—seaward—side of the fault.

There is another point of some importance which is illustrated by the model. When the left-hand frame f_1 is moved upwards by means of the screw, the strips of steel are not only bent but are subjected to tensional force, so that it would be impossible to keep the vertical rods together if it were not for the lateral play allowed to the right-hand frame f_2, which permits of its approximating to the other. In Nature, the distortion giving rise to such a tensile force is not so marked; for the gradual movement of one portion of the earth's crust relatively to the other is usually small, compared with the width of the tract of ground between them that suffers deformation: but it must have an important influence in determining the occurrence of fracture in a region of strain, as rocks offer but feeble resistance to tension. In areas where the earth's crust is in a state of tension and normal faulting occurs, the tendency to fracture will be greater and faults more numerous. On the other hand, in regions characterized by reversed faults where tangential compression is present, this will play the same part as the movement of the right-hand frame, and tend to diminish the tendency to fracture, so that it will only be when movements are very considerable or take place with comparative rapidity that faults will result: in other cases they will be replaced by folds. The same region may, of course, be at one time affected by compression and at another by tension.

On these principles it is easy to understand why normal faults should be more frequent than reversed faults, despite the fact that we have every reason to believe that conditions involving pressure more commonly prevail than those resulting in tension.

Discussion.

Mr. R. D. Oldham said that the model was certainly very instructive, so far as it reproduced the effects observed after the Californian earthquake; but, with regard to the cause of the earthquake so little was known, and the impossibility of reproducing the conditions in Nature was so obvious, that no model could convey information or prove anything. The Author had adopted and illustrated a theory which was generally accepted, but which the speaker himself had found reason to abandon for the supposition that great earthquakes are as a rule due to the sudden development of strain, or what might be crudely described as an explosion, rather than the sudden relief by fracture of a slowly accumulating strain. This, however, did not affect the use of the Author's model as an illustration of the deformation which may be the result of an earthquake.

The AUTHOR said that he was strongly opposed to the views of the school of seismologists, to which Mr. Oldham had, it seemed, now given his adherence, who thought that the great earthquakes represented explosions of igneous material in the earth's crust (misslungene Ausbruchsversuche, to use the expressive phrase of Branca). Such earthquakes as were known to be due to explosive volcanic action were local in character, and had little effect on distant seismographs. Important earthquakes like the Californian earthquake of 1906, as well as the majority of the smaller disturbances, appeared to be closely related to lines of tectonic weakness, and it was reasonable to suppose that they were incidents of the readjustment of the earth's crust, which is always proceeding, though more active in some periods than in others.

He would like to add that a sudden explosion of an imprisoned magma could only occur in the neighbourhood of the surface. It was dynamically impossible under the pressure of a great thickness of superincumbent strata.