The Character and Cause of Earthquakes.[1]

By R. D. OLDHAM, F.R.S.

THE character of earthquakes, that is, of the disturbance which can be felt and causes damage, has long been established as a form of elastic wave motion, originated by some sudden disturbance in the substance of the earth. In some cases, such as the Japanese earthquake of 1891 or the Californian of 1906, the earthquake was accompanied by visible fractures and displacements of the solid rock, and where these have been observed it has also been noticed that the violence of the disturbance reached its maximum close by, and became less as the distance from the fracture increased. From this it is evident that, in such cases at least, the earthquake originated from the jar caused by sudden rupture of the rocks, and the fault, or fracture, may be regarded as the cause of the disturbance to which the earthquake was due. In many other cases, where no actual faulting or fracture is visible at the surface, and especially in earthquakes of moderate intensity and extent, a study of the observations makes it very probable that the immediate cause of the disturbance was a fresh movement along an old fault, or the formation of a new one, and so may be found in many text-books the statement, put forward and elaborated, that faults are the cause of those earthquakes classed as tectonic. Thus it might seem that the cause of earthquakes had been explained, but this is only the beginning of the story, for we need to know what causes the fracture which gives rise to the earthquake.

In pursuing this object, reference may be made to an earthquake which occurred more than a hundred years ago, at a time when the observation of earthquakes was in its infancy, and when little information of present value could be expected, had it not been for certain peculiarities in the country affected, and in the effect of the earthquake. Just beyond the north-western angle of the Indian Peninsula lies one of the most extraordinary regions of the world, known as the Runn of Cutch; more than 200 miles in length, and some 30 in width, it is a level barren plain, so flat and so near the sea-level that when the waters of the sea are heaped up, by the south-west monsoon, and the streams from the surrounding country come down in floods, the greater part of the surface is covered with a sheet of water, varying from a few inches to five or six feet in depth.

The whole of this region, however, has not always been so barren as at present, for, up to the seventeen hundreds, a large river, fed by the waters of the Punjab, and by overflow from the Indus, flowed down through Eastern Sind, across the Runn to the Kori creek, and on the banks of this river were fertile and populated tracts; also on this river was situated a frontier fort of the Government of Cutch, where customs duties were collected. Then, in the eighteenth century, through changes in the river courses far inland, the supply of water in this river began to fail, and a series of bunds, or what we would now call barrages, was built to hold up the water and divert it for irrigation. Towards the end of the century, the whole of the water supply was intercepted, and the region below relapsed into a state of desolation; but the fort of Sindri was still maintained, with a small garrison and a few officials to collect the dues, and so things continued until June 16, 1819, when the classic earthquake of Cutch occurred.

The fort of Sindri was not only ruined, but the ground on which it lay was also lowered in level, water flowed in from the sea, and the small garrison of Sindri saved themselves from drowning by taking refuge in the main tower, whence they were rescued by boat the next day. Nor was this subsidence the only change noticed, for, about four miles to the north, where before had been only a dead level plain, the survivors observed a long low mound, stretching east and west with a height of about 20 feet, along the northern edge of the flooded area. This mound, so like an artificial embankment, was immediately named the "Allah Bund" or "God's Barrage," on the same principle which named the bunds or barrages higher up the stream after the names of their makers.

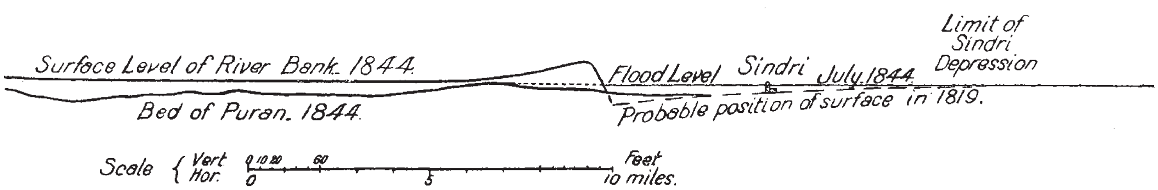

FIG. 1.—Section across the Allah Bund and Sindri depression of June 16, 1819.

Ten years later, the ruins of the fort were seen still standing out of a waste of waters, and twenty-five years later, in 1844, a careful survey was made and levels taken, and this survey revealed a remarkable condition of things (Fig. 1). From the north the surface of the delta sloped southwards, at about eight to ten inches in the mile, to within six miles from the crest of the Allah Bund, when a reverse slope was met, and the surface gradually rose to nearly 20 feet above the level of the continuation of the southerly slope, or the level at which it presumably stood before the earthquake. Thence there was a steep slope downwards, to the water of the Sindri lake. On the south the original reports mention a depth of twelve feet of water close to the shore, immediately after the earthquake, and, as the original surface level must have been a few feet above that of the sea, we have a depression of some fifteen feet, which gradually died out in a distance of some six miles to the southward. From these facts it is clear that there was no appreciable change of level at a distance of about six miles on either side

[1] Condensation of a course of two lectures delivered at the Royal Institution on January 30, February 6.

of the line of the Allah Bund, but that along that line the ground on the north was upraised by some twenty feet and on the south depressed by some fifteen at the time of the earthquake.

The next earthquake to be considered is one which has been investigated with great care and in great detail; it is the Californian earthquake of April 18, 1906. In this there was a visible fracture, following what is known as the San Andreas fault, along which the shock attained its maximum intensity. This fracture was crossed at various points by roads and fences, and after the earthquake it was noticed that, where these crossed the line of fracture, they were no longer continuous, but the ends were shifted laterally by distances which varied at different places, but frequently amounted to twenty feet. This was not all, for the displacement was of a very curious nature, revealed by surveys of the displaced fences, and by a repetition of the original trigonometrical survey of the region. These showed that for a distance of some miles back from the fault line the stations had been displaced, those nearest to the line by the greatest amount, which lessened as the distance increased and, at about five miles or so to the east, became very small. Moreover, it was found that the movement on the eastern side of the fault had been to the southwards, and on the western towards the north.

Here we have a result very like that in Cutch; in both cases there was a well-defined line along which permanent change of position of the ground took place, simultaneously, in opposite directions on either side of the line of separation, and in both cases the displacement decreased in amount with increasing distance, till it ceased to be measurable at a distance of about half-a-dozen miles. The only difference was that in California the displacements were horizontal, with little or no change of level, while in Cutch they were vertical, whether accompanied or not by horizontal shifting cannot be known.

Paradoxical though it may seem, this movement on opposite sides of the fracture in opposite directions is quite in accord with known physical principles. If any block of material is compressed or stretched in one way, while free to expand or contract in a transverse direction, or if it is twisted by two opposite sides being forced in opposite directions, a complicated system of strain is set up, and if the strain is more than the material will bear, disruption will take place, on opposite sides of which the material will move in opposite directions.

Models to illustrate this principle have been constructed by others and myself, and from these considerations there has arisen what is known as the elastic rebound theory of earthquake origin, and as generally expressed this takes the form of a very slow growth of strain and a sudden release by fracture. The former, however, is by no means necessary, and the same result, as regards displacements of the ground, would be attained if the strain was rapidly, even suddenly, produced. There are, in fact, reasons for supposing that the growth of strain is not slow but rapid, yet the fracture and elastic rebound theory might be accepted as sufficient, if earthquakes could always be attributed to a single fracture, or to a close-set group of fractures; but in the case of great earthquakes, and sometimes of minor earthquakes also, the interpretation is put out of court by a study of the distribution of the intensity of the disturbance.

In illustration I may take first the great Indian earthquake of June 12, 1897, in which the central region of greatest intensity covered an area of about 140 miles long by 40 miles broad, over which there was a complicated series of faults, fractures, and distortion, which was certainly widely different from the comparatively simple origin generally assumed for earthquakes. This seemed at the time sufficient to account for all the facts, though there were some recorded as difficult to explain, and later examination seems to have established the conclusion that the origin of the earthquake cannot be limited even to this extensive area. In this earthquake only two of the isoseists could be plotted in detail, those of eight degrees and of two, or the extreme limit at which the shock could be felt; both exhibit considerable irregularities of outline, the most conspicuous of which is a pronounced projection to the westwards, and on the continuation of this line is a detached area, where the shock was again felt, after a gap where it was not felt. Col. Harböe has suggested, from a study of the recorded times, that there was an extension of the origin along this line, and though his plotting of the origin cannot be accepted in detail, I am convinced that, in the main, his conclusions are correct, for they very materially help to explain some peculiarities of the recorded observations, which remained inexplicable on the older and more generally used interpretation.

From this it appears that in earthquakes covering a large area we are not dealing with a simple disturbance, starting from an origin of restricted dimensions and propagated outwards, but with one of complex origin; and that in the outer regions of the seismic area the disturbance may be compounded of wave motion propagated from a more or less distant origin, where the initial severity was great, and of that coming from a nearer origin, of a lesser degree of severity, so that, instead of a fracture of at most a few tens of miles in length, we have to deal with a cobweb-like system of fractures, or something analogous, which may run to hundreds of miles.

The general drift of the argument I wish to set forth is probably best illustrated by the California earthquake of 1906. In this the greatest degree of violence was found along the line of the San Andreas fault, but the plotting of the isoseists shows that there was not only an independent centre in the San Joaquin valley, some forty miles to the eastwards, but also several independent centres of great intensity at lesser distances from the San Andreas fault. Moreover, the displacements recorded by trigonometrical survey make it probable that other similar independent centres would be found to the west, if the waters of the ocean had not made observation impossible. The records, therefore, indicate a set of separate centres of disturbance, scattered over a region of about three hundred miles in length by very possibly one hundred miles in width, and these separate centres, though independent as regards the surface shock, were all evidently connected with some common cause. Had they been the result of breakage under a slowly growing strain it is difficult to understand how so complicated, scattered, and extensive a series of fractures could have originated simultaneously, but it is, to say the least, much less difficult to understand if the development of strain over the whole of the central area had been sudden, or at any rate rapid.

Then there is another point to be noticed, that in the central region the successive isoseists lie close together, while in the outer fringe they lie far apart; thus the distance separating the isoseists of ten and seven degrees, covering a range of three degrees of intensity, varies from 6 to 20 miles on either side of the San Andreas fault, while in the outer regions a similar range of three degrees covers from 120 to 250 miles. The close-set isoseists of the central region indicate a shallow origin, and such is proved by the San Andreas rifts, where the origin reached the surface of the ground; the widely set outer isoseists similarly indicate a deep-lying origin: and so we reach the conclusion that the earthquake origin was of a two-fold nature, the great violence in the central region being due to fractures and displacements close to, or at a comparatively shallow depth below, the surface, and that these fractures were the secondary result of a more deep-seated disturbance or bathyseism.

Having reached this conclusion there remain two questions of importance, what is the depth, and what is the nature of this bathyseism? As to the depth, the study of a remarkable, though only feeble, earthquake which affected northern Italy on August 7, 1895, has led me to conclude that the ultimate origin lay at 100 to 150 miles below the surface; but the best indications are to be had from the long-distance records of disturbances, which need not necessarily have been great earthquakes, in the ordinary sense of the words.

From these Dr. L. Pilgrim, in 1913, deduced the conclusion that the origin of the disturbance, in the case of the Californian earthquake, lay at a depth of about 100 miles, and, more recently, a similar method has been developed in this country by Prof. H. H. Turner, who has shown that the long-distance records indicate depths of origin ranging from fifty to three hundred miles below the surface of the earth. Now it seems fairly well established that earthquakes of quite shallow origin do not give rise to distant records, even when very violent in the place where they are felt, and it is probable that the disturbance recorded by these distant seismographs is not the superficial destructive earthquake, but the bathyseism.

Next comes the question of the nature of the bathyseism. That it must be in some way accompanied by a change in bulk of the material underlying the central area of the earthquake, seems clear, in some cases at least. Fracture such as is sufficient to explain most of the features of the surface shock seems out of the question, for the depths place it in the region of what it is nowadays the fashion to call the asthenosphere, that is, a part of the earth which is weak and plastic against stresses of long duration; but as regards change of bulk, recent researches have indicated one very likely mode in which it might be brought about. It is known that the foundation rocks of the outer crust are everywhere composed of an aggregate of crystalline minerals, the detailed study of which shows that the material must once have been in a condition analogous to that of fusion, from which it has solidified by cooling to its present condition. Further, it has been shown that the same original magma may crystallise out as quite different mineral aggregates, differing in density, and therefore in volume, by anything up to 20 per cent. The exact conditions which determine the passage from one form of chemical grouping to another are not known in detail, but it is probable that in each case there is some critical limit of temperature and pressure which determines it. If there were, in the interior of the earth, a mass of material near this critical limit, a small change of pressure or temperature might bring about a change of chemical combination, and with it a greater or lesser change of bulk, which, transmitted to the upper layers of the earth's crust, would give rise to displacements and distortion. Such changes might be unaccompanied by earthquakes, if they were slow and gradual, or, if rapid or sudden, might give rise to fractures in the surface rocks, of greater or lesser magnitude, and covering a larger or smaller area, according to the bulk of the deep-seated material undergoing a change of volume.

Without insisting on this as the nature of the bathyseism, and it is possible that other causes as yet unsuspected may also be at work, it is evident that we have an explanation which would suffice in the case of the larger, and of many of the smaller earthquakes. Yet there are some causes, perhaps no inconsiderable fraction of the total, in which the whole process leading up to the earthquake seems to lie quite close to the surface. To these, always small in extent, though sometimes of considerable severity, the consideration which I have outlined cannot at present be applied; in part they must be due to quite different causes, the consideration of which is not without interest, but this interest only arises after more extended and technical study than could be presented, even in outline.

Hydrogen Ion Concentration.

By Prof. A. V. HILL, F.R.S.

CERTAIN solutions are capable of conducting electricity, although their separate pure components are themselves incapable, or capable only to a slight degree, of so doing. This conductivity is attributed to the "ionisation" of the dissolved body, that is, to the splitting up of its molecule into two or more parts, some carrying a positive and others a negative charge, the resulting "ions" being capable of migration under an imposed electric field, and so giving to the solution the power of carrying a current. The electrically neutral molecule breaks up into (*a*) a negatively charged part, containing an excess of electrons which lend it its negative charge, and (*b*) a positive portion with a deficit of electrons, this deficit resulting in an equal positive charge. These positive and negative ions attract one another, as do all positive and negative charges, and are separable only if their mutual attraction be small enough to be overcome by the inter- and intra-molecular dynamic forces (not yet properly understood) tending to their separation.

The attraction between two charges is far greater if they be separated by some media than by others, to a