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Founders of Seismology.—II. Robert Mallet.

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WHILE Michell's interest in geology lasted until at least 1788, he made no further known contribution to the study of earthquakes. He must have been aware of the disastrous Calabrian earthquakes of 1783, but he would no doubt regard them as timely illustrations of his theory. The eighty years which followed 1760 were, indeed, somewhat barren as regards the progress of seismology. Among the more important contributions during this period were Dolomieu's report on the Calabrian earthquakes of 1783, Darwin's memoir on the connexion of certain volcanic phenomena in South America (1838), and the well-known chapters in Lyell's *Principles of Geology* (1830).

About the year 1840 a new period began, a period of rapid progress, during the first forty years of which the outstanding figures were those of Alexis Perrey in France and Robert Mallet in England. A brief reference should, however, be made to the work of David Milne (afterwards Milne Home) on the earthquakes of Great Britain, and especially on the remarkable series of Comrie earthquakes, which began in October, 1839, and lasted for the next six years.[1]

The work of Alexis Perrey was almost concurrent with that of Mallet, Perrey's lasting from 1841 to 1875, and Mallet's from 1845 to 1878. Perrey was professor of mathematics at Dijon. Except for his seismic bibliography (1855–65) and his papers on the relation between the frequency of earthquakes and the age of the moon (1853, 1861, and 1875), he devoted himself to the heavy and uninspiring task of cataloguing earthquakes. His catalogues were of two kinds, chronological and geographical. The former consist of lists of earthquakes in all parts of the world for each year from 1843 to 1871. The regional catalogues, seventeen in number, cover the whole of Europe, with the exception of Russia, Scandinavia, Denmark, and Germany outside the basin of the

[1] *Edin. New Phil. Journ.*, vol. xxxi, 1841, pp. 92–122, 259–309; vol. xxxii, 1842, pp. 106–27, 362–78; vol. xxxiii, 1842, pp. 372–88; vol. xxxiv, 1843, pp. 85–107; vol. xxxv, 1843, pp. 137–60; vol. xxxvi, 1844, pp. 72–86, 362–77.

Rhine. Of the other continents, only special regions are considered—in Asia, the Philippine Islands, Japan, and the Kurile Islands and Kamschatka; in Africa, Algeria and the north of the continent; in America, the Antilles, Chile, Peru, and the Aleutian Islands, Alaska, etc. Regarding the interior of the earth as fluid, it was only natural that Perrey should investigate a lunar periodicity[1] in the occurrence of earthquakes, but his three laws of greater frequency at syzygies than at quadratures, at perigee than at apogee, and, for any place, when the moon crosses the meridian, can hardly be regarded as possessing a firm foundation. His chief claim to our gratitude rests on his extensive catalogues. Our knowledge of the history of nearly every seismic region of the globe depends at one point or another on the untiring labours of Alexis Perrey.

In other respects the ground was unoccupied. Our knowledge of individual earthquakes was gradually increasing, the facts of earthquake phenomena were becoming known, but, as yet, there was no science of seismology. The next step was made, not by a trained student, but by a busy practical engineer; and when we think of the work which Mallet accomplished for seismology we should also remember that it was done, for the most part alone and unaided, in the midst of great engineering enterprises.

Robert Mallet was born at Dublin on June 3, 1810, his father, John Mallet, being the proprietor of a factory in which sanitary fittings and small fire-engines were made. At the age of 16 Mallet entered Trinity College, Dublin, taking the degree of B.A. after a four years' course. In the following year (1831) he married and was taken into partnership in his father's factory. This he soon converted into engineering works with a considerable foundry, and before many years had passed all the engineering work of any consequence in Ireland was carried out by the firm. Mallet's first great feat was to raise the roof of St. George's Church, Dublin, a mass 133 tons in weight, and covering a large area. This was followed by the building of several bridges over the Shannon, and the invention and construction of hydraulic rams and of ventilating and heating apparatus for public buildings. His buckled plates, which he began to make in 1840, form one of the best floors ever designed, combining the maximum of strength with the minimum of depth and weight. They are to be found on the Westminster and other London bridges. In 1845–6 he was erecting a railway station while he was working at his first important paper on the dynamics of earthquakes. In 1849–55 he built various station roofs, and the Fastnet Rock lighthouse, and was designing heavy guns and large mortars, the latter capable of throwing 36 inch shells. At the same time he

[1] It is interesting to notice that the possibility of a lunar periodicity occurred to Darwin in 1840. Writing to D. Milne, he remarks, "On the hypothesis of the crust of the earth resting on fluid matter, would the influence of the moon (as indexed by the tides) affect the periods of the shocks, when the force which causes them is just balanced by the resistance of the solid crust?" (*More Letters of Charles Darwin*, vol. ii, 1903, p. 115).

was writing his British Association reports on the facts of earthquake phenomena, determining the velocity of earth-waves in sand and solid rock, and compiling his catalogue of recorded earthquakes. In 1859 he wrote a valuable paper on the coefficients of elasticity and rupture in wrought iron, and at about the same time worked out the results of his investigation of the Neapolitan earthquake of 1857, and made further experiments on the velocity of earth-waves at Holyhead.

In 1861, engineering work becoming scarce in Ireland, Mallet moved to London, where he set up as a consulting engineer and edited the *Practical Mechanic's Journal.* After an active and healthy life his eyes began to fail during the winter of 1871–2, and he was practically, though not quite, blind during the last seven years of his life. He died on November 5, 1881.

"In scientific thought, Robert Mallet was remarkable for the originality of his ideas, and for the broad grasp he took of every subject that engaged his attention; in private and social life he was beloved for the kindness, geniality and humour of his disposition, for his readiness in conversation and uniform good temper."[1]

Until he was about 35 years old, Mallet, like Michell, had apparently given no thought to earthquakes. His attention was drawn to them, not by a great disaster, but almost by accident. He had noticed in Lyell's *Principles* the well-known diagram of a pair of pillars, the upper parts of which had been twisted, without being overthrown, by one of the Calabrian earthquakes. He saw at once the flaw in the usual statement that, under each pillar, there must have existed an independent vorticose movement. His practical training suggested a simple mechanical explanation. If the centre of adherence of the base of the twisted portion were to lie outside the vertical plane containing its centre of gravity and the direction of the motion, the result might be the observed rotation.[2] The problem is one of minor importance. Its interest lies chiefly in the fact that its solution led Mallet to the views on the nature of earthquake-motion which he described in his memoir on the dynamics of earthquakes.[3]

In this memoir, in addition to the discussion of the problem referred to, Mallet considers the nature of the earthquake-motion in the earth's crust, the nature and origin of seismic sea-waves and of earthquake sounds, the need and use of observations on the

[1] *Roy. Soc. Proc.*, vol. xxxiii, 1882, pp. xx. For the above biographical details I am chiefly indebted to notices in *Engineering*, vol. lii, 1881, pp. 352–3, 371–2, 389–90; and *Min. of Proc. of Inst. of Civ. Eng.*, vol. lxviii, 1882, pp. 297–304.

[2] Other, and perhaps more probable, explanations of the movement are given in *Trans. Seis. Soc. Japan*, vol. i, pt. ii, 1880, pp. 31–5, and GEOL. MAG., 1882, p. 264.

[3] "On the Dynamics of Earthquakes; being an attempt to reduce their observed phenomena to the known laws of wave motion in solids and fluids" (read February 9, 1846): *Trans. Irish Acad.*, vol. xxi, 1848, pp. 51–105.

velocity of earth-waves, and the advantage of founding earthquake observatories in various parts of the world. There is perhaps little that is really novel in the whole memoir, little, if anything, that the present-day student of seismology would have occasion to consult, and his account of Michell's work is strangely inaccurate and incomplete. Its chief merit is that it does form an attempt to explain the more important phenomena of earthquakes by the light of one guiding principle, and thus, as he says, to bring them within the range of exact science. As W. Hopkins wrote in the following year, he treated the subject " in a more determinate manner and in more detail than any preceding writer ".

The principle referred to is that an earthquake is " the transit of a wave of elastic compression in any direction, from vertically upwards to horizontally, in any azimuth, through the surface and crust of the earth, from any centre of impulse, or from more than one, and which may be attended with tidal and sound waves dependent upon the former, and upon circumstances of position as to sea and land ".[1] At the same time, he realized that the waves of vibration may " become complicated by movements of permanent elevation or depression in the land . . . the effects of which it may often be difficult or impossible subsequently to separate."

Mallet gives a very full description of the sea-waves which accompany earthquakes. Although he does not follow Michell in separating the visible waves from the waves of vibration on land, he distinguishes two kinds of sea-waves—the forced sea-wave, as he calls it, and the great sea-wave. His explanations of the origin of both are partially incorrect. The forced sea-wave, which accompanies the earth-waves and is " carried upon its back, as it were ", is merely the wave of compressional vibrations in water. If the great sea-wave, which sweeps in some time later, were initially raised by the earth-wave, there would be a great sea-wave with every strong submarine earthquake. He does, however, notice that the sea-wave may become " complicated by movements of permanent elevation or depression in the land ", and to this extent his explanation is no doubt correct.

Great stress is laid on the importance of determining the velocity of the earth-wave, not so much for the interest of the question in itself, as on account of its geological applications. Mallet was aware that the velocity in any rock must depend on the elastic constants of the rock. If we were to measure these constants for all the different rocks, the knowledge of the velocity in a given submarine earthquake, he suggested, would enable us to predict

[1] Many earlier writers had regarded earthquakes as due to the passage of waves of vibration, e.g. J. Michell in 1760, Thomas Young in 1807 (*Lectures on Natural Philosophy*, vol. i, p. 717), and D. Milne in 1841 (*Edin. New Phil. Journ.*, vol. xxxi, pp. 262, 275–7). In his report on the theories of elevation and earthquakes (*Rep. Brit. Assoc.*, 1847, pp. 33–92), W. Hopkins, treating the theory as obvious or well known, gives an account of wave-motion in solids and liquids that may still be read with advantage.

the nature of the underlying rock-formations—an anticipation which has not, I am afraid, so far been fulfilled.

In his early views on the origin of earthquakes Mallet was in advance of his time. He connects earthquakes with "local elevations of portions of the earth's crust, often attended with dislocation and fracture of the crust, and sometimes attended with the actual outpouring of liquid matter from beneath." He imagines an earthquake to be produced "either by the sudden flexure and constraint of the elastic materials forming a portion of the earth's crust, or by the sudden relief of this constraint by withdrawal of the force, or by their giving way, and becoming fractured". Where should we look for such sudden changes? Not in volcanic countries, he thinks, but rather in that broad sub-oceanic belt within which the deposits of the land are accumulated and from which they may afterwards be swept away by tidal currents. "Such a condition of the sea-bottom would seem to be the most likely state of things to give rise to frequent and sudden local elevations or even submarine eruptions of molten matter." And he notices that, while earthquakes are frequent in volcanic countries, they are never of the greatest violence. On the other hand, "the centre of disturbance of almost all the greater earthquakes appears to be beneath the sea, and at considerable distances from active volcanoes," while "the circumstances of the great sea wave seem to indicate that the centre of disturbance is seldom, if ever, *very* distant from the land".

I have given a somewhat full account of this important memoir, for whatever its imperfections may be it must, I think, be regarded as the chief foundation-stone of seismology as a science. Fortunately Mallet did not rest content with this, practically his first, contribution. He became afterwards widely known to the scientific public by his four reports to the British Association on the facts of earthquake-phenomena, their publication covering most of the years from 1850 to 1858. His crowning work on the Neapolitan earthquake of 1857 was published in 1862. With this report and with his memoir on the velocity of earth-waves at Holyhead, his career as a seismologist practically ended, for his study on volcanic energy lies outside our range, and his later papers, owing to his practical blindness, were of minor value. After his first memoir Mallet's work may thus be considered under the following headings: (i) experiments on the velocity of earth-waves; (ii) the preparation and discussion of the catalogue of recorded earthquakes; (iii) the development of methods of investigating earthquakes; and (iv) their application to the study of the Neapolitan earthquake.

Velocity of Earth-waves.—As already remarked, Mallet attached great importance to accurate determinations of the velocity of earth-waves. His first experiments were made in two widely differing materials—the wet sand of Killiney Bay, on the coast of Co. Dublin, and the granite of the neighbouring Dalkey Island. In Killiney Bay charges of 25 lb. of gunpowder were exploded in the sand, and the passage of the waves at a distance of half a mile was detected by the tremors on the surface of a mercury bath. In Dalkey Island the ranges were of less than half this length (1021–1155 feet), the granite in one set being of a more fissured or shattered character than that in the other. The mean of eight measurements in sand, six in the fissured granite and three in the other, gave the following velocities, after all corrections were applied :—

Sand	825 feet per second.
Discontinuous granite	1,206 ,, ,, ,,
More solid granite	1,665 ,, ,, ,,

The second series of measurements were made at Holyhead from 1856 to 1861, large masses of rock being dislodged from the Government quarries by the explosion of from one to five or more tons of gunpowder in mines. The ranges (six in number) varied from slightly less than a mile to about a mile and a quarter, crossing different lengths of quartz rock, slates, and schists. The velocities varied from 954 to 1,289 feet per second, the average of all six measurements being 1,089 feet per second.[1]

Catalogue of Recorded Earthquakes.—In the compilation of his earthquake catalogue, as well as in the experiments described above, Mallet was assisted by his eldest son, the late J. W. Mallet. The catalogue forms his third report on earthquake-phenomena, and occupies nearly six hundred pages in the reports of the British Association. The discussion of the catalogue and the description of the seismic map of the world are contained in the fourth report.[2] Though based on several earlier catalogues—especially those of Von Hoff, Cotte, Hoffman, Merian, and Perrey—Mallet regarded his catalogue as probably the first attempt to include all recorded earthquakes. The labour involved in its preparation must have been immense. From scattered sources—books of travel, British, French, and German newspapers and scientific journals—the number of entries obtained amounted to about one-half the total number. The details relating to each earthquake are given in tabular form under the six headings : time of occurrence, area chiefly affected, the direction, duration, and number of the shocks, great sea-waves, etc., meteorological and secondary phenomena, and the authorities for the records. The first entry is under the date 1606 B.C., and Mallet originally proposed that the catalogue should end with the year 1850. It was found, however, that the completeness of Perrey's annual catalogues rendered its extension beyond the year 1842 unnecessary, but the earthquakes of the eight omitted years are included in the discussion of the fourth report. The total number

[1] *Rep. Brit. Assoc.*, 1851, pp. 272–317; *Phil. Trans.*, 1861, pp. 655–79; 1862, pp. 663–76. The above velocities are given to the nearest foot per second. Mallet expresses them to three places of decimals. Such detail, however, is meaningless, for an error of one-hundredth of a second in the time of transit at Killiney Bay involves an error of more than 2 feet per second in the velocity.

[2] *Rep. Brit. Assoc.*, 1852, pp. 1–176; 1853, pp. 118–212; 1854, pp. 1–326; 1858, pp. 1–136.

of earthquakes recorded is stated by Mallet to be 6831, of which 216 were " great " earthquakes, or strong enough to reduce whole towns to ruins. Judging from the last 150 years, during which the record of such disasters may be supposed complete, Mallet estimates that a great earthquake occurs on an average once every eight months. The rapid expansion in the number of entries, especially during the last three centuries, is no proof, in Mallet's opinion, of any actual increase in earthquake-frequency. He regards it as, in fact, " a record of the advance of human enterprise, travel, and observation," the evidence tending rather to the conclusion that " during all historic time the amount of seismic energy over the observed portions of our globe must have been nearly constant." At the same time, there is clear evidence of irregular and paroxysmal outbursts of energy in reference to shorter periods. The frequency curves for the last three centuries and a half (1500–1850) show, indeed, that while the least interval of repose may be a year or two, the average interval is from five to ten years ; that the shorter intervals are usually connected with periods of diminished earthquake frequency ; that the alternations of paroxysm and repose appear to follow no discernible law ; except that two marked periods of extreme paroxysm occur in each century, the greater about the middle and the less not far from the end.

Still more important are Mallet's conclusions on the distribution of earthquakes in space. Previous seismic maps of the world, such as those in the physical atlases of Berghaus and Johnston, were based on imperfect catalogues. In neither, as he notices, is there any attempt made to depict by various tints the greater or less frequency and violence of earthquakes in different areas. Mallet's materials were much fuller, though still far from complete. The original map, on Mercator's projection, is 75 inches long and 48 inches wide (reduced in the report to about one-third linear dimensions). He divided earthquakes into three classes—great, mean, and minor. If their disturbed areas were unknown, he assumed that their radii were 540, 180, and 60 geographical miles, and their areas were coloured by three tints, the intensities of which were as the numbers 9, 3, and 1. Thus, the most deeply shaded areas on the map represent those in which earthquakes are most frequent and violent.

While its defects are obvious, Mallet's map remained for nearly half a century our best representation of the distribution of earthquakes over the globe. The more important results which he deduced from it are the following : as the distribution of earthquakes is paroxysmal in time, so also it is local in space ; the normal type of distribution is in bands of variable and great width (from five to fifteen degrees) ; these bands very generally follow the lines of elevation which divide the great oceanic or terr-oceanic basins of the earth's surface ; in so far as these are frequently the lines of mountain-chains, and these latter those of volcanic vents, so the seismic bands are found to follow them likewise ; the regions of least or no disturbance are the central areas of great oceanic or terr-oceanic basins and the greater islands existing in shallow seas. The modern and more accurate method of mapping by epicentres, rather than by disturbed areas, has led to greater detail in our knowledge, but the main laws of seismic distribution are those which Mallet has so clearly established.

Methods of Investigation.—Though they are not explicitly stated, there can be little doubt, I think, that the methods of investigation which Mallet afterwards developed, were partly present in his mind when he wrote his early papers. Even in the first edition (1849) of the *Admiralty Manual of Scientific Inquiry,* to which, on Darwin's recommendation, he was invited to contribute, there is no direct account of them in the section on the observation of earthquake phenomena. They are described for the first time, and very fully described, in his report on the Neapolitan earthquake, and it is some indication of the importance which he attached to them that the main title which he gave to these two large volumes is " The First Principles of Observational Seismology ".

The fundamental object of Mallet's inquiry was to ascertain the surface-position and depth of the seismic focus. The methods which he proposed for this purpose are well known. By observations on the direction of fissures in large and uniform buildings, of the fall of columns, and of the projection of detached masses of masonry, he sought to determine the azimuth or horizontal direction of the shock, and such directions at two or more places would suffice to determine the position of the point vertically above the seismic focus, which we now know as the epicentre. Once this point is determined, a single observation of the angle of emergence, as given by the inclination of fractures in walls, would lead to the depth of, at any rate, one point within the focus.

Various writers before Mallet had suggested the use of observations on the direction of the shock. The earliest case known to me, which I have already quoted (p. 105), is that of J. Michell, in 1760. D. Milne used the method in 1841 to determine the epicentre of the Comrie earthquakes, which were at that time frequent, the directions at different places being obtained chiefly from the records of inverted pendulums. He also made the valuable suggestion that " if instruments could be invented which at different places would indicate, not merely the relative intensity of the shocks, but the direction in which they acted on bodies, means would be obtained of determining the point in the earth's interior from which the shocks originated "[1]—a method which, forty years later, occurred to J. Milne, and was used by him, and afterwards by Omori and Hirata, to determine the depth of the seismic foci of some Japanese earthquakes. Lastly, W. Hopkins, in giving (1847) the same method for locating the epicentre, adds the important remark that the direction observed should be that at

[1] *Rep. Brit. Assoc.*, 1841, p. 48; 1842, pp. 96–7; 1843, p. 121; *Edin. New Phil. Journ.*, vol. xxxi, 1841, pp. 276–7.

the first instant of the motion, for, afterwards, the later vibrations of the condensational wave and the earlier vibrations of the distortional wave may coalesce—a precaution which lies at the root of Galitzin's method.[1] It is one thing, however, to suggest a method, and a very different matter to apply it; and few, I think, will be found to deny that, if any name is to be associated with these methods, it should be that of Robert Mallet.

Study of the Neapolitan Earthquake of 1857.—Owing to his long residence in Ireland—a typical aseismic country—Mallet had no direct acquaintance with earthquakes until 1852. On November 9 of that year he was awakened by a strong shock, one that is perhaps unique among British earthquakes in having affected all four portions of the United Kingdom. It failed, however, to give him the materials that he required, and five years more had to pass before they were provided by the Neapolitan earthquake of December 16, 1857. Leaving Naples on February 10, he spent several weeks visiting the ruined towns and villages of the meizoseismal area, heedless of the many discomforts of a camp life during the wet and cold of winter, convinced that in fractured walls and overthrown pillars he had " the most precious data for determining the velocities and directions of the shocks that produced them ", inspired by the thought that for the first time the depth of the seismic focus was being " measured in miles and yards with the certainty that belongs to an ordinary geodetic operation ". Sixty years have passed since then; the certainty of 1858 may have given way to doubt; yet, as one reads the account of his work at Polla and Vietri di Potenza, when he realized that at last he had found the point vertically above the origin of the shock and could state, as a first approximation, that the depth of the focus was 5·64 geographical miles, one cannot but sympathize with his confidence that he was showing the way to a true intelligence of " the viewless and unmeasured miles of matter beneath our feet ".

Mallet's report on the Neapolitan earthquake is the first of a long series of monographs on shocks of special strength or interest, and for forty years, until the Assam earthquakes of 1897, it remained without a rival. His map of the earthquake marks an epoch in seismology. For the first time isoseismal lines were drawn on such a map. There are four of these. The first surrounds the meizoseismal area, within which the towns were for the most part prostrated; the second includes places in which large parts were thrown down and persons were killed; the third those in which slight damage to buildings occurred without any loss of life; while the fourth bounds the area within which the shock was perceived by the unaided senses.

On this map Mallet also depicted the lines of wave-path at different places, taking the most probable mean direction when more than one was measured. The majority of the observations he found to

[1] *Rep. Brit. Assoc.*, 1847, pp. 82–3.

pass within a circle, 2½ geographical miles in radius, with its centre close to the village of Caggiano. Of twenty-six separate wave-paths, twenty-three start from the vertical line through this centre at depths of less than 7⅛ geographical miles. The mean depth of the focus he estimated at 5¾ geographical miles, and the probable vertical dimension of the focal cavity at about 3 geographical miles. Some of the azimuths, however, pass outside the Caggiano circle. From their various points of intersection Mallet concluded that the focal cavity was a curved fissure 9 geographical miles in horizontal length. The mean velocity of the earth-waves he found to be 788 feet per second. The amplitude and maximum velocity of the vibrations naturally varied greatly. At Polla, which is close to the epicentre, he estimated the amplitude at 2½ inches, and the maximum velocity at 13 feet per second.[1]

Conclusion.—To sum up Mallet's contributions to seismology is not an easy task. One of the most important is also the most intangible—his influence on the different points of view from which earthquakes were regarded, say in 1845 and after the lapse of twenty years. Fifteen years after his death and nearly forty years after the Neapolitan earthquake, I was struck by the fact that of more than two thousand observers of the Hereford earthquake of 1896, one in every five gave unasked the direction of the shock. In the large towns the proportion rose to one in every three.

"It is given to no man," said Mallet, "so to interpret nature that his enunciation of her secrets shall remain for ever unmodified by the labours of his successors." Mallet's work was unfortunately no exception to this rule. Some of it may now be obsolete, but much of it remains. Several of the terms in daily use—seismology, seismic focus, angle of emergence, isoseismal line, and meizoseimsal area—are due to him. The position of the epicentre may still be determined by observations on the direction of the shock, especially by the mean of a large number of observations. As regards the depth of the focus, the results derived from such observations are much less certain. All that can be said is that they perhaps indicate the order of magnitude of the true depth. His experiments on the velocity of earth-waves are interesting, though their bearing on the actual problem is somewhat remote. But, by his perception of the nature of earthquake-motion, by the construction of isoseismal lines, by the compilation of his great catalogue, by his statement of some of the laws which govern the distribution of earthquakes in time and space, and, above all, by his investigation—the first rational investigation—of a great earthquake, Mallet has placed the science of seismology under a debt, which those who have followed in his steps would be the last to underestimate.

[1] A more detailed account of Mallet's investigation is given in my *Study of British Earthquakes* (Contemporary Science Series), pp. 7–44.