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be placed under irrigation.* Means could in all probability be found for restoring to cultivation large areas between Lake Chad and Borku. In the bed of the Bahr el Ghazel wells already exist and their number could be increased by boring. Efforts to regenerate the intermediate zone are, naturally, likely to take second place to the development of the richer regions further south, but work in that zone has the recommendation that it will form a protection against further encroachment by the desert.

As to mineral wealth the Sahara is rich in salt. Phosphates, potash, and soda are found; the great beds of phosphates exploited in Algeria and Tunisia lie on the Saharan border. There is a regular export of potash from Air to Nigeria. Gold and precious minerals were mined by the ancient Egyptians in the hills facing the Red Sea and gold-mining on a small scale has begun again in the Nubian Desert. Soda in large quantities is obtained from the Natron lakes west of Cairo, from the Chad district and other regions. Petroleum-bearing strata are believed to exist. But the mineral resources of the Sahara are practically unknown, though the belief that they are great is probably well founded.

When all has been done for the economic development of the Sahara which is possible, when France, Great Britain, and Italy between them maintain peace throughout its wide extent, when a population ten times as numerous as it now is finds in it means of support, the desert will in outward aspect be little altered. It will remain a land of immense solitudes and boundless horizons, of strange dead mountains and dry riverbeds, of verdant oases, waving palms and ever-receding mirages—a land of heat and thirst, of rock and dune, in which the tents of the nomads and the caravans of camels will leave a more lasting impression than the lines of steel which bind it anew to the outer world.

EARTHQUAKES IN GREAT BRITAIN (1889-1914).

By CHARLES DAVISON, Sc.D., F.G.S.

DURING the twenty-six years considered in this paper the total number of known earthquakes is 357. The average annual number is thus 13·7, or slightly more than one a month. The annual number, however, is extremely variable. No year was entirely free from earthquakes, though in each of three years (1897, 1899 and 1914) only one earthquake is recorded and in each of three others (1895, 1902 and 1913) only two. Some years were unusually rich in earthquakes, 18 shocks being felt in 1908 and 1909, 19 in 1891, 20 in 1892, 21 in 1910, 23 in 1901 and 1906, 26 in 1890, and 74 in 1912.

The more important earthquakes as well as many of the slighter

* See 'Haut-Sénégal-Niger. Géographie Economique,' by J. Meniaud. Paris, 1912.

shocks (altogether 130 in number) occur sporadically in different parts of the country, seldom visiting the same district except at long intervals, and differing chiefly from the great earthquakes of seismic countries in their slighter intensity and in the greater duration of the intervals of quiescence. They include such strong earthquakes as those of Inverness in 1890 and 1901, Pembroke in 1892 and 1893, Hereford in 1896, Derby in 1903 and 1904, Carnarvon in 1903, Doncaster in 1905, and Swansea in 1906. These 10 earthquakes which, with their associated shocks, account for 77 of the 130 earthquakes originated in at least eight different seismic centres. The Derby earthquakes originated in the same double focus, the Inverness earthquakes probably in the same focus. There are also a few other districts in each of which two or three earthquakes of minor importance originated. Otherwise each of the centres responsible for the above earthquakes has been disturbed only once during the twenty-six years and indeed for many years before 1889.

The remaining earthquakes (227 in number) are of somewhat unusual character. They belong to two series of shocks closely resembling those which during the last century made the name of Comrie famous. They are of special frequency for this country, rarely attaining any considerable strength except near their centres, and originating for the most part beneath an area of not more than a few square miles. The earlier series of 41 earthquakes occurred in Glen Garry in Invernesshire from 1889 to 1899; the later, of 186 earthquakes, in the district bordering the southern slope of the Ochil Hills between the years 1900 and 1914. Throughout the period considered the Comrie centre has been almost in a state of quiescence, only three slight earthquakes having been recorded, in the years 1894, 1895 and 1898.

METHODS OF INVESTIGATION.

It may be convenient if I give here a brief account of the methods of investigation which I have used in studying British earthquakes. The methods are based on the modern view as to the origin of earthquakes, that they are for the most part the result of tectonic operations and especially of the growth of faults. No recorded British earthquake has ever been accompanied by perceptible crust-displacements at the surface. We may therefore look upon our earthquakes as the transitory effects of the waves of vibration generated as one rock-mass adjoining a fault slides over and against the other.

In such cases the seismic focus (or region within which the initial impulse is produced) is a portion of the fault-surface. For our present purpose it may be regarded as a plane surface inclined to the horizon, and, as a rule, of much greater dimensions in the horizontal than in the vertical direction. In the simplest case the relative displacement of the rock-masses adjoining the fault is greatest in the central portion of

the focus and decreases gradually towards the margins until it dies away.

Determination of the Originating Fault.—It is evident that a focus of such a form and position must affect the distribution of intensity on the surface of the ground. This distribution is represented by means of isoseismal lines, or lines passing through all places at which the maximum intensity of the shock is the same, the intensity being usually determined by reference to an arbitrary scale, such as the modification of the well-known Rossi-Forel scale given below. Conversely, from the forms of the isoseismal lines it should be possible to infer the direction of the originating fault, its hade or the direction in which it is inclined, and approximately the course of the fault-line on the surface. Also, from the dimensions of the isoseismal lines we may form a rough estimate of the horizontal length of the seismic focus. It will be sufficient here to state the conditions which determine the elements of the originating fault. They are as follows :

1. When the isoseismal lines are much elongated the direction of their longer axes is approximately the direction of the originating fault.

2. On the side towards which the fault hade the isoseismal lines of a weak earthquake are farther apart than on the other side ; those of a strong earthquake are farther apart at a short distance from the epicentre and closer together at a great distance.

3. The fault-line must be nearly parallel to the axis of the innermost isoseismal, at a short distance from it and on the side of it opposite to that towards which the fault hade.

4. The length of the seismic focus is approximately equal to the difference between the length and width of the inner isoseismals.

The Exmoor earthquake of January 23, 1894, may be offered as an example of these methods. The shock was a slight one, in no place of intensity higher than 4 (see the scale of intensity given below). The two curves on the map (Fig. 1) represent isoseismal lines of intensities 4 and 3, the latter forming the boundary of the disturbed area. Both curves are elongated ellipses and their longer axes are parallel, being directed E. 22° S. The isoseismal 4 is $22\frac{3}{4}$ miles long and $12\frac{1}{4}$ miles wide, the isoseismal 3 is $29\frac{3}{4}$ miles long and $16\frac{1}{2}$ miles wide, the distance between the curves being $1\frac{1}{4}$ miles on the north side and 3 miles on the south side. The originating fault must therefore run on an average in the direction E. 22° S., it must hade toward the south, and the fault-line must pass a short distance to the north of the centre of the isoseismal 4. Its probable course is represented by the broken line on the map.

A short time after the earthquake occurred the late Dr. Hicks published his first paper on the "Morte Slates" (*Quart. Journ. Geol. Soc.*, vol. 52, 1896, pp. 254-272). "A great thrust fault," he says, "extends continuously along the northern boundary of the Morte Slates, from the coast near Ilfracombe to the Exe Valley. On the south side there is

evidence generally also of a well-marked fault." These faults hade towards the south. In the map (Fig. 1) they are represented by continuous lines as far as they are shown in Dr. Hicks' first paper. If the northern fault were to bend round as shown by the dotted line and then continue as represented by the broken-line, it would satisfy all the seismic conditions. Without knowing the real course of the fault I sent my map to Dr. Hicks and he returned it with the course as mapped by him, which coincided almost exactly with that suggested by the seismic evidence. This coincidence thus seems to support both the theory of the origin of earthquakes and the methods of investigation based on it.

Scale of Seismic Intensity.—The scale which I have used in studying

FIG. 1.—EXMOOR EARTHQUAKE OF JANUARY 23, 1894.

British earthquakes is founded on the well-known Rossi-Forel scale. The number of tests is reduced to one for each degree, thus allowing the isoseismal lines to be drawn with greater accuracy than is attainable in a less thickly populated country, in which single tests might result in insufficient observations. The following is the scale:—

1. Recorded only by instruments.
2. Felt only by a few persons lying down and sensitive to weak tremors.
3. Felt by ordinary persons at rest.
4. Windows, doors, fire-irons, etc., made to rattle.
5. The observer's seat perceptibly raised or moved.
6. Chandeliers, pictures, etc., made to swing.

7. Ornaments, vases, etc., overthrown.
8. Chimneys thrown down and cracks made in the walls of some, but not many, houses in one place.
9. Chimneys thrown down and cracks made in the walls of about half the houses in one place.

The first seven degrees of this scale correspond to the same degrees of the Rossi-Forel scale, and the last two to degree eight of that scale.

Sound-Phenomena.—Considerable use is made of the sound-phenomena in studying British earthquakes. The principal sound-vibrations are close to the lower limit of audibility, a limit, moreover, which is variable in different persons, so that in one place and even in the same house the sound may be heard by some observers and be inaudible to others who are equally attentive. The percentage of audibility, or the percentage of persons who hear the sound within a given area, declines on the whole as the distance from the epicentre increases, slowly at first, very rapidly as the boundary of the sound-area is approached. It does not depend, however, only on the distance, and the decline in audibility is therefore represented by means of isacoustic lines, or lines drawn through all places within which the percentage of audibility is the same.

DESCRIPTION OF SOME TYPICAL EARTHQUAKES.

I will now give brief descriptions of some earthquakes which may be regarded as typical of British earthquakes in general. The earthquakes selected are the Inverness earthquake of 1901, the Ochil earthquakes of 1900-1914, the Hereford earthquake of 1896, and the Derby earthquake of 1903. It will be seen that the first two and the last two are representative, respectively, of the two chief classes of British earthquakes.

1. *Inverness Earthquake of September 18, 1901.*—This earthquake, one of the strongest of all Scottish earthquakes, disturbed the whole of Scotland with the exception of the southern counties. The isoseismal lines (corresponding to intensities 8-4 of the scale given above) are represented by the curves in Fig. 2. Within the isoseismal 8 many houses were slightly damaged; near its centre, which is about two or three miles south-west of Inverness, walls were cracked and chimneys thrown down. The outermost curve (an isoseismal of intensity 4) bounds the disturbed area, which is 215 miles long from north-east to south-west, 198 miles wide, and includes within it about 33,000 square miles, an area approximately equal to that of Ireland.

Throughout the whole of this area the shock was almost uniform in its nature. At Inverness, for instance, there was first a gentle movement followed by a quivering which increased in force for two or three seconds and then decreased for two or three seconds; just as this quivering was about to cease there was a distinct heave, after which the vibration was much more severe than before. The shock thus consisted of a single series of vibrations with two maxima of intensity, of

which the second was the stronger. At some distance from the epicentre the intermediate tremors were imperceptible and the shock consisted of two parts corresponding to the two maxima observed at Inverness.

The innermost isoseismal (that of intensity 8) is an ellipse 12 miles long and 7 miles wide, with its longer axis directed N. 33° E. The isoseismal 7 is $53\frac{1}{2}$ miles long and 35 miles wide, its longer axis being

FIG. 2.—INVERNESS EARTHQUAKE OF SEPTEMBER 18, 1901.

parallel to that of the isoseismal 8. The distance between the two curves is 9 miles on the north-west side and 14 miles on the south-east side. It may be inferred that the originating fault runs parallel to the longer axes of these curves, that it fades (or is inclined) to the south-east, and that the fault-line lies a short distance on the north-west side of the centre of the isoseismal 8. The chief fault of the epicentral district is the great boundary-fault which runs from Tarbat Ness along the eastern

coast of Ross-shire, and follows the line of the Great Glen. The mean direction of the fault is about N. 35° E., its hade is to the south-east, and the fault-line passes about three-quarters of a mile to the north-west of the centre of the isoseismal 8. It thus agrees with all the conditions demanded by the seismic evidence.

The earthquake was preceded by a slight shock on September 16 and followed by at least seventeen after-shocks. The centres of the innermost isoseismals of the more important of these shocks are represented by the dots in Fig. 3, *a* being that of the fore-shock, *B* that of the principal shock, and *c, g, h, m, n, q*, those of the stronger after-shocks. The continuous line shows the course of the great fault. It will be noticed that all these centres lie within a narrow band which is parallel to the fault-line and lies on the side of it towards which the fault hade, thus confirming the conclusion that the earthquakes were due to slips along the great fault.

The great slip which caused the principal earthquake must have been at least 5 or 6 miles in length, reaching nearly from Loch Ness to Inverness. The fore-slip of September 16 occurred near the south-west extremity of the principal focus. Taking into account only the stronger after-shocks there were, within three hours of the great slip, two (*c* and *g*) near the south-west margin of the principal focus. About two hours later the next important slip (*h*) took place on the north-east side of the principal centre, probably extending the focus in that direction. For more than eleven days there was no movement of any consequence. On September 29 a small slip (*m*) occurred about one mile to the south-west of the principal centre, followed in six hours (on September 30) by a long slip (*n*) to the south-west of the principal focus and extending

FIG. 3.—CENTRES OF INVERNESS EARTHQUAKES OF 1901.

two or three miles beneath Loch Ness. The last important after-shock (*q*) occurred on October 13 a short distance on the south-west side of the principal centre. Besides the lateral migration of the after-shock centres there was also a continual approach (from $1\frac{1}{2}$ miles to $\frac{1}{10}$ mile) of these centres towards the fault-line, indicative of a decreasing depth in their foci. Thus the results of the great slip which caused the principal earthquake were increases of strain in the marginal regions of the principal focus, and in the portion of the fault above the centre of the focus. The minor slips which resulted from these increased strains thus occurred for the most part in the terminal and central portions of the principal focus, but especially towards and underneath the north-east end of Loch Ness.

2. *Ochil Earthquakes of 1900-1914.*—This remarkable series of earthquakes began on September 17, 1900, and ended on December 18, 1914. The total number of earthquakes included in it is 186, the annual numbers being 4 in 1900, 1 in 1903, 10 in 1905, 19 in 1906, 13 in 1907, 17 in 1908, 18 in 1909, 19 in 1910, 8 in 1911, 74 in 1912, 2 in 1913, and 1 in 1914. The series includes three strong earthquakes, those of September 21, 1905, October 20, 1908, and May 3, 1912. The intensities of these shocks were respectively 6, 7 and 7, and their disturbed areas about 1000 and not less than 600 square miles. Besides these there were 10 earthquakes which disturbed areas ranging from 74 to 136 square miles, the average being about 94 square miles. Of the remaining 173 earthquakes 24 were earth-sounds without perceptible tremor, 101 were of intensity 3, 34 of intensity 4, and 8 of intensity 5, the disturbed area in no case exceeding 60 square miles and being usually much less.

The isoseismal lines of one of the more important shocks (that of September 21, 1905) are represented in Fig. 4. The inner isoseismal is 13 miles long and 8 miles wide, with its longer axis directed E. 29° N., the distance between this isoseismal and the next being $3\frac{1}{4}$ miles on the north side and $2\frac{3}{4}$ miles on the south side. In the 10 earthquakes of intermediate strength the boundary of the disturbed area closely resembled the isoseismal 6 in Fig. 4. There is some variation in the direction of the longer axes of the isoseismal lines, the limiting values being E. $7\frac{1}{2}^{\circ}$ N. and E. 29° N., and the average direction E. 19° N. In the stronger earthquakes the isoseismal lines are farther apart towards the north than towards the south. The weakest shocks of all are felt only in one or more of the villages which lie along a line joining Airthrey and Alva; in the earthquakes of intermediate strength the greater part of the disturbed area lies on the north side of this line. It may therefore be concluded that the average direction of the originating fault is about E. 19° N., that it must have trended to the north, and that the fault-line must lie a short distance to the south of the centres of the innermost isoseismals. The well-known fault at the base of the Ochil Hills, the course of which is shown in Fig. 4, satisfies very nearly two of these

conditions. Its mean direction in the epicentral district is E. 13° N., and the fault-line passes through or near the villages mentioned. The direction of its hade is unknown from the geological evidence. There can be little doubt, from the seismic evidence, that its hade is towards the north.

A remarkable feature of the Ochil earthquakes is their great intensity, taking into account the smallness of their disturbed areas. For instance, the principal earthquakes of 1908 and 1912 were both of intensity 7,

FIG. 4.—OCHIL EARTHQUAKE OF SEPTEMBER 21, 1905.

and their average disturbed area was less than 1000 square miles. The average disturbed area of all the other earthquakes of the same intensity during the years 1889-1914 is 31,000 square miles. We are therefore led to the conclusion that the seismic foci of the Ochil earthquakes must lie at a very slight depth below the surface.

Another feature of some consequence is the brevity of the shock and sound. When the shock is of intensity 4 or higher it usually consists of one or two prominent vibrations followed, and occasionally preceded, No. V.—NOVEMBER, 1915.]

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by a brief tremor. When the shock is of intensity less than 4 the prominent vibrations are absent and the shock consists of a brief tremor only. The sound also is usually referred to types of brief duration, the percentage of comparison with such types being 47 for the three principal earthquakes, 54 for those of intermediate strength, and 73 for the slightest earthquakes. We may infer from these results that the focus is usually of small dimensions ; and this conclusion is supported by the measurements of the inner isoseismals which give an average of 5 miles for the principal earthquakes and 4 miles for those of intermediate strength.

The portion of the fault along which slips have occurred during the first fourteen years of this century is about 10 miles in length. In order to study the migration of the foci along the fault we may divide this portion into five regions—a central region from Menstrie to Alva, an eastern region near Tillicoultry, a western region near Airthrey, Bridge of Allan and Dunblane, and east-central and west-central regions between the central and terminal regions.

Taking first the three principal earthquakes, that of 1905 originated in the eastern region, that of 1908 in the east-central region, and that of 1912 in the west-central region. Thus, regarding the greater movements only, there was a continual westerly migration of activity. Considering the minor shocks alone this migration is also evident. With the exception of the first two principal shocks, none occurred in the eastern and east-central regions. Throughout the whole period they occurred frequently in the central, west-central, and western regions, predominating in the central region before the principal earthquake of 1912 and in the western region afterwards.

3. *Hereford Earthquake of December 17, 1896.*—Though exceeded in destructiveness by the Colchester earthquake of 1884, no known British earthquake has disturbed so large an area (98,000 square miles) as the Hereford earthquake of 1896. This area, with five isoseismal lines (of intensities 8-4), is shown in Fig. 5. The isoseismal 8 is an elongated ellipse, 40 miles long and 23 miles wide, with its longer axis directed N. 46° W. It includes within it 73 places where marked damage occurred to buildings, the injury to houses being greatest at Hereford and some of the surrounding villages, all lying within a small area near the north-west focus of the ellipse. The distance between the isoseismals 8 and 7 being 20 miles on the north-east side and 13 miles on the south-west side, it follows that the originating fault must be directed about north-west and must have trended to the north-east.

In nearly all parts of the disturbed area the shock consisted of two distinct series of vibrations separated by an interval of about 2 or 3 seconds of absolute rest. The two series, however, differed in intensity and duration. The first series of vibrations was the stronger and of greater duration in the north-west portion of the disturbed area, and the second series in the south-east portion. Moreover, the boundary

between these two portions was not a straight line perpendicular to the longer axes of the isoseismal lines, but, as represented by the broken-line on the map, slightly curved, the concavity facing the south-east. This curve also forms the axis of a narrow band within which the shock was continuous, the two series of vibrations being felt simultaneously.

The only conclusion that can be drawn from these observations is that the seismic focus consisted of two detached portions. One of these, the more important, was evidently in the neighbourhood of Hereford, its

FIG. 5.—HEREFORD EARTHQUAKE OF DECEMBER 17, 1896.

centre being about 3 miles south-east of that city; the other was probably about 2 or 3 miles north-east of Ross, the distance between the centres of the two foci being about 9 miles. As the surface-band within which the two parts of the shock coalesced is concave to the south-east, it follows that the Hereford focus was first in action, as the vibrations from it had to travel farther than those from the Ross focus before coalescing with them. Also, since the two series of vibrations were superposed at places within the curved band, it is clear that the Ross

focus was in action before the vibrations from the Hereford focus had time to reach it—otherwise, the latter vibrations would have been felt everywhere before the former. Thus, though due to a single generative effort, the impulses in the two foci occurred independently and almost simultaneously, the interval between them being not more than 2 or 3 seconds. On this account the Hereford earthquake belongs to the class which I have called twin earthquakes.

These conclusions are confirmed in a remarkable manner by the observations on the sound-phenomena. Within the whole disturbed area 59 per cent. of the observers recorded their perception of the earthquake-sound, the percentages of audibility varying from 87 in the central county of Hereford to 23 in Essex. The audibility of the sound did not, however, depend entirely on the distance from the centre, as will be seen from the dotted lines on the map, which represent isacoustic lines corresponding to audibility-percentages of 80, 70, 60, and 50. The distortion of the isacoustic lines in the neighbourhood of the curved band is clearly due to the coalescence of the sound-vibrations from the two parts of the focus, the effect of the coalescence being obviously a higher percentage of audibility.

From the orientation and relative positions of the inner isoseismal lines it may be inferred that the originating fault runs approximately north-west and south-east, and fades to the south-east, and that the fault-line must pass a mile or less to the south-west of Hereford. Now to the north-east of this position lies the well-known Woolhope anticlinal the axis of which runs about north-west and south-east. Moreover the thinning out and occasional disappearance of some of the Silurian beds on the south-west side of the anticlinal suggests that there must be a fault or rapid flexure at or near the junction of the Old Red Sandstone and Silurian strata. If a fault, it must fade to the north-east. It would thus satisfy two of the conditions required by the seismic evidence, but the fault-line would lie a mile or two to the north-east. Thus the Hereford earthquake must have been caused by a movement along a parallel fault lying a mile or two to the south-west, or possibly along the fault referred to, but at a considerable depth, the fault-plane assigned by the seismic evidence being a tangent-plane to the fault-surface at the depth of the focus.

4. *Derby Earthquake of March 24, 1903.*—The isoseismal lines of this earthquake (corresponding to intensities 7, 6, 5, and 4) are represented by the continuous lines in Fig. 6. The disturbed area contains about 12,000 square miles. The inner isoseismal (intensity 7) is 38 miles long and 28 miles wide; its longer axis is directed N. 33° E., and the distance between the isoseismals 7 and 6 is 12 miles on the north-west side, and 8 miles on the south-east side. The originating fault must therefore run in a direction about N. 33° E., must fade to the north-west, and must pass a short distance to the south-east of Ashbourne. There is no known fault in this position.

As in the Hereford earthquake the shock consisted of two distinct parts, nearly equal in intensity and separated by an interval of three seconds of rest. The double shock was noticed in all parts of the disturbed area, except within a narrow rectilinear band, the boundaries of which are represented by broken lines on the map. This band, which is about 5 miles wide, runs centrally across the inner isoseismals in a direction at right angles to the axes of those isoseismals.

It is evident that the double shock was due to two distinct impulses

FIG. 6.—DERBY EARTHQUAKE OF MARCH 24, 1903.

occurring in detached foci arranged along a line parallel, or nearly so, to the isoseismal axes; that the two impulses were nearly equal in intensity; and that, as shown by the straightness and central position of the single-shock band, the two impulses occurred at exactly the same instant. The positions of the two epicentres cannot be determined exactly, but from the form of the isoseismal lines it is probable that one lay close to Ashbourne, and the other about 3 miles west of Wirksworth. The distance between the centres of the two foci must therefore be about 8 or 9 miles.

These conclusions are again supported by the evidence of the isacoustic lines corresponding to audibility-percentages of 95 and 90. As will be seen from the dotted lines on the map both curves are distorted in the direction of the rectilinear band, their axes being almost coincident with this band.

The principal earthquake was followed by three after-shocks, the first two of which were extremely slight, and took place on the same day. The third occurred on May 3, the shock being of intensity 5. The disturbed area contains about 585 square miles. The isoseismal lines are ellipses roughly concentric with and parallel to the isoseismal 7, their longer axes being in the direction N. 25° E. From the relative position of the isoseismal lines the originating fault must have been to the north-west. There can therefore be little doubt that the after-shock originated in the same fault as the principal earthquake, and in the region lying between the two foci of that earthquake.

CLASSIFICATION OF BRITISH EARTHQUAKES.

The preceding descriptions show that British earthquakes may be divided into two distinct classes, namely simple and twin earthquakes. Simple earthquakes consist of a single series of vibrations, usually with one, but sometimes with two or more maxima of intensity. Twin earthquakes consist of two series of vibrations, separated by an interval of two or three seconds, which is generally one of complete rest and quiet.

The modes of origin of simple and twin earthquakes will be considered in a later section of this paper. It will be sufficient to state here that of the 357 earthquakes of the period considered, only 11, or about 3 per cent. belong to the class of twin earthquakes. Also that of the 9 earthquakes in which the isoseismal 4 included an area of more than 10,000 square miles, 2 were simple and 7 twin earthquakes, the latter including the strongest earthquakes felt in this country.

DISTRIBUTION OF BRITISH EARTHQUAKES.

Of the 357 earthquakes felt during the years 1889 to 1914, 51 occurred in England, 27 in Wales, 279 in Scotland. In Ireland not a single earthquake is known to have originated, though 5 Welsh or English earthquakes were felt across the Irish Channel. Thus as regards number only Scotland holds the first place; and the inequality is still greater if the area of the countries be taken into account, as then for every 10 earthquakes occurring in England, there are 37 in Wales, and 94 in Scotland. If, however, the intensity of the strongest earthquakes be considered the inequality is reversed. Thus of the 9 earthquakes in which the isoseismal 4 included an area exceeding 10,000 square miles, only 1 occurred in Scotland, while 4 occurred in England and 4 in Wales. Again, while in the Inverness earthquake of 1901 this area amounted to 33,000 square miles, in the Pembroke earthquake of 1893 it amounted to 35,900 square miles, in the Swansea earthquake

of 1906 to 37,600 square miles, in the Pembroke earthquake of 1892 to 44,860 square miles, and in the Hereford earthquake of 1896 to 98,000 square miles.

The earthquakes of Scotland are remarkable in other respects besides frequency. They are invariably simple earthquakes, twin earthquakes being confined to England and the south of Wales. The great majority can be assigned with some degree of confidence to well-known faults. And lastly, these faults belong for the most part to one system of fractures: that to which the name Caledonian is usually applied, the direction of which is roughly north-west and south-east. For instance, the northern boundary-fault of the Highland district, which traverses Scotland in a south-westerly direction from Tarbet Ness through Inverness, is connected with 17 of the 19 Inverness earthquakes of 1901, with some, if not all, of the 11 Inverness earthquakes of 1890, and possibly with 5 slight earthquakes in the neighbourhood of Fort William. The southern boundary-fault of the same district, which traverses Scotland from Stonehaven to the southern end of Loch Lomond, is responsible for the three Comrie earthquakes; and the fault which skirts the southern slope of the Ochil Hills (though trending more in an easterly direction) with 186 shocks. Again, the two Edinburgh earthquakes of 1889, the Kintyre earthquakes of 1889 and 1890, the Strontian earthquake of 1902, and the Dunoon earthquakes of 1904 and 1908, are connected with faults which run roughly in a north-easterly direction. The faults to which the 41 Glen Garry earthquakes of 1889-1899 and the three Annandale earthquakes of 1894 and 1896 are to be assigned are unknown, owing to insufficient records. The only known exceptions are the Loch Broom earthquake of 1892, which was due to a movement along a fault directed N. 30° W., and the two Glasgow earthquakes of 1910 caused by movements along a fault running nearly east and west.

In Wales slight shocks are rare unless they occur as accessory shocks of strong earthquakes, the only exceptions being the Bala earthquake of 1903 and the Beddgelert earthquake of 1904. The origin of the latter earthquake is unknown, as are also the origins of five of the Pembroke earthquakes of 1892. Of the remainder the principal Pembroke earthquake of 1892 and at least three of its after-shocks were connected with Malvernian faults, having a general north and south direction; two of the after-shocks of that earthquake, as well as the strong Swansea earthquake of 1906 and its after shock of 1907, and probably the four Pembroke earthquakes of 1893, with Armorican faults, having a general east and west direction. The eight Carnarvon earthquakes of 1903 and 1906 are associated with the Aber-Dinlle fault, and the Bala earthquake of 1903 with the great Bala fault, both faults belonging to the Caledonian system. In the Welsh earthquakes of 1889-1914, the Charnian system of faults (north-westerly in direction) is entirely unrepresented.

In England the epicentres are somewhat widely distributed; 13 lie

in Herefordshire (all connected with one fault), 10 in Cornwall, 8 in Derbyshire (connected with one fault), 5 in Yorkshire, 4 in Cumberland, 3 in Leicestershire and Somerset, and 1 in Devon, Lancashire, Worcestershire and Westmorland. The Californian system of faults is responsible for 15 earthquakes, the Charnian for 21, the Malvernian for 7, and the Armorican for 5. Seventeen faults (nearly all in Palæozoic rocks) have been in action, 12 with simple earthquakes, and 5 with twin earthquakes. Of these faults only three have been recognized by geological evidence, two being connected with simple earthquakes, and one with twin earthquakes.

ORIGIN OF BRITISH EARTHQUAKES.

The close connection between the earthquakes and faults of Great Britain will be obvious from the preceding pages. It is not in all cases possible to associate particular earthquakes with well-known faults. This is only to be expected, seeing that the faults with which we are acquainted by geological evidence are those which traverse the superficial rocks. The investigation of earthquakes, indeed, throws light on the structure of portions of the earth's crust which are far below the regions that are accessible to the field-geologist; and it seems to indicate that the structure of these deeper layers is much less complex than that of the surface strata.

Into the nature of the connection between the earthquakes and the originating faults it is hardly necessary to enter. The subject is fully discussed in my little volume on the 'Origin of Earthquakes' (Cambridge Manuals of Science and Literature). But it may be remarked that all the faults with which British earthquakes have been associated are faults of great antiquity, and that the earthquakes can only be due to the *growth* of those faults, that is, to fault-slips by which the throw of the fault is changed. The friction which results as one rock-mass slides over and grates against the other is the originating impulse of the earthquakes.

In simple earthquakes the fault-displacement is of the simplest possible character. One rock-mass is displaced relatively to the other over a continuous area which is several or many miles long in a horizontal direction. This area constitutes the seismic focus. The amount of displacement may not, in any part of the focus, exceed a fraction of an inch, and it dies out both upwards and laterally. The result of this displacement is a sudden increase of strain in the marginal regions of the focus and in the portion of the fault immediately above the focus. And this increase of strain may be, and often is, sufficient to precipitate minor slips, each of which gives rise to an after-shock. Thus, as in the case of the Inverness earthquake of 1901, the after-slips should take place especially towards the terminal regions and in the portion of the fault above the central region of the principal focus. Each minor slip, however, increases the strain to a similar, but less, extent in its surrounding regions. Thus there may be a continual migration of the seismic

foci until the increased resulting strains are insufficient to overcome their resistances opposed to them. The series of earthquakes then comes to an end, and a state of quiescence ensues, which lasts until the growing strains are once more great enough to precipitate movement.

Twin earthquakes, as we have seen, are due to slips within two detached foci. The two slips are so nearly simultaneous that they must be regarded as independent, that is, one is not a consequence of the other. At the same time, both slips must be due to a single generative effort, for it is inconceivable that two independent slips should occur so closely together as regards both time and space. Simple displacements being thus out of the question, the only other movement that can account for twin earthquakes is one of rotation; and, in the formation of crust-folds, and especially along their intersection by transverse faults, it is evident that such movements must be taking place. For instance, in Fig. 7 the

FIG. 7.—ORIGIN OF TWIN EARTHQUAKES.

continuous line is supposed to represent a stratum of a crust-fold, of which C is the crest, T the trough, and M the middle limb. The broken-line represents the same stratum after a step in the growth of the fold. The result of such a movement will clearly be displacements, nearly or quite simultaneous, in two detached foci C and T, with an intermediate region of little or no displacement in that portion of the middle limb M about which rotation has taken place.

After the occurrence of such a twin-displacement the strains along the margins of both foci are immediately increased, especially in the interfocal region of the middle limb. In consequence of this increased strain twin earthquakes are usually succeeded, after a few hours or days, by an after-shock originating in the interfocal region; and, as these after-shocks are always simple earthquakes, it follows that they are caused by simple displacements, without rotation, of the middle limb, say from the position represented by the broken-line in Fig. 7 to that represented by the dotted line. But since the after-shock is always weaker than the twin earthquake, it is clear that the translation of the middle limb is much less in amount than the previous displacements of the crest and trough. Thus the movements which cause a twin earthquake and its successor result

(1) in accentuating the form of the crust-fold, and (2) in a relative advance of one portion of the crust-fold cut off by the transverse fault.

If this theory of the origin of twin earthquakes be correct there should be some correspondence between the distance between the epicentres of the earthquakes and the distance between successive crests and troughs of the great crust-folds. For British crust-folds this distance is unknown; but for the principal folds in France the average distance in different districts varies between 9 and 12 miles. As the average distance between the epicentres of British twin earthquakes is about 10 or 11 miles, the agreement is sufficiently close.

Between simple and twin earthquakes there is thus an important difference, not only as regards their nature but also as regards their origin. Also to this difference in their origin there corresponds a difference in the nature of the fault to the growth of which they are due. Leaving out of account the after-shocks of twin earthquakes, it would seem that simple earthquakes are usually, almost invariably, due to displacements along strike-faults, while twin earthquakes are due to displacements along transverse faults.

Lastly simple earthquakes can usually be referred to well-known faults; in twin earthquakes the originating fault is almost invariably unknown, though in some cases the direction and hade agree with those of neighbouring faults, but differ by a mile or two in the position of the fault-line. The reason of this difference is probably that simple faulting along a strike-fault is a comparatively superficial phenomenon, while the growth of a fold along a transverse fault is much more deeply seated. In the latter case the fault-surface determined by the seismic evidence is, strictly speaking, a tangent-plane to the fault at a considerable depth, and this tangent-plane does not of necessity intersect the surface of the earth along the same line as the superficial portion of the fault-surface which is known to geologists.

GEOGRAPHY AT THE BRITISH ASSOCIATION.

THE meeting of the British Association at Manchester this year differed, as was indeed fitting, from previous meetings of the Association. The proceedings, instead of lasting for a week as is the custom under normal conditions, began on Tuesday, September 7, and in most sections were concluded on the following Friday. As social functions, however, were practically in abeyance more time was available for scientific work, and in Section E at least the time devoted to papers and discussions was not appreciably less than in former years. The meeting was not a large one (1400 members and associates as against 3800 when the Association last met in Manchester in 1887), but its success from the scientific point of view has led to the suggestion that the Association should revert to its earlier practice and abandoning all social activities should confine itself to purely scientific work.

In one respect Section E suffered as a result of the war. Its President, Major H. G. Lyons, F.R.S., was prevented from attending by pressure of Government