

24. *THE INVERNESS EARTHQUAKE OF SEPTEMBER 18TH, 1901, and its ACCESSORY SHOCKS.* By CHARLES DAVISON, Sc.D., F.G.S. (Read April 16th, 1902.)

[PLATES XI & XII.]

I. INTRODUCTION.

THE earthquakes of Inverness and Comrie, though never so strong as those of Essex and Hereford, bear, in their long trains of after-shocks, a far closer resemblance to the great earthquakes of other countries. Since the Comrie earthquake of October 23rd, 1839, which was followed by 330 tremors and earth-sounds within little more than two years,<sup>1</sup> no British earthquake has been attended by so many accessory shocks as that which occurred in the neighbourhood of Inverness on September 18th, 1901. The unusual intensity of the earthquake, its apparent connection with the great northern boundary-fault of the Highlands, and the possibility of tracing oscillations in successive centres of disturbance along the fault-surface, combined in rendering a detailed investigation desirable.<sup>2</sup> The names of all those who have assisted me are too numerous to mention here; but, in offering my best thanks to them collectively, I should like to acknowledge my special indebtedness to Mr. W. J. Watson, Rector of the Royal Academy, Inverness, Mr. A. S. Reid, F.G.S., of Trinity College, Glenalmond, Mr. S. Archibald of Dalarnessie, and Miss Isabel Forbes of Teanassie, near Beauly, for the most useful series of accounts which they have kindly collected. Valuable records of after-shocks have also been communicated to me by the following gentlemen:—Mr. D. Forsyth (Inverness), Mr. James Fraser (Aldourie), Mr. John E. Fraser (Dores), Mr. P. Fraser (Holm, near Lentrán), Mr. A. Grant (Drumalan, near Drumnadrochit), Mr. W. Grant (Invermoriston), Mr. R. Keillar (Lochend, Aldourie), Mr. W. Mackenzie (Bunchrew), Lieut.-Colonel L. D. Mackinnon and Mr. D. Munro (Dochgarroch), Lieut.-General F. W. Peile (Inverness), Mr. D. A. Rose (Abersky), and the Rev. T. Sinton (Dores); while Col. Mackinnon and Mr. D. Munro have furnished some interesting notes with regard to the fissure formed in the bank of the Caledonian Canal, near Dochgarroch.

In the following catalogue of earthquakes, I have included no records but those made by careful observers. A large number (41) of the shocks and earth-sounds rest on the authority of a single observer; but, while all are probably of seismic origin, I have distinguished by means of prefixed letters and more detailed descriptions, those (19 in number) that were noticed by several or many persons.

In estimating the intensity of the shocks, I have referred as usual

<sup>1</sup> J. Drummond, *Phil. Mag.* vol. xx (1842) pp. 240–47.

<sup>2</sup> The expenses of the investigation were defrayed from a grant received from the Government Research Fund.

to the Rossi-Forel scale, but have employed only one test for each degree.<sup>1</sup> At the head of the account of each earthquake, the position of the epicentre is given to the nearest tenth of a minute of latitude and longitude; and, in the account itself, I have stated the approximate position with reference to Dochgarroch, a place which lies close to the epicentres of nearly all the shocks. In the maps (Pls. XI & XII), the isoseismals are indicated by continuous lines when some confidence may be placed in their accuracy; and, in parts, by broken lines when their course is doubtful, owing to the scarcity or absence of observations.

As the principal earthquake occurred shortly after midnight, many of the observers were asleep when it began. In most cases, however, they were evidently awakened by the preliminary sound; for, according to those who were awake, the beginning of the sound preceded that of the shock in 72 per cent. of the records, coincided with it in 21, and followed it in 8 per cent. According to those who were asleep, the corresponding figures were 72, 20, and 9. In other respects, also, the two classes of observers differ but slightly; and the only point on which I have not availed myself of the evidence of those who were at first asleep, is the relative intensity of the two parts of the shock.

## II. FAULTS OF THE EPICENTRAL DISTRICT.

With a few exceptions, the earthquakes originated beneath the district lying between Inverness and the north-eastern end of Loch Ness. The chief structural feature of this 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 this fault is about N. 35° E., and S. 35° W., and its hade is to the south-east. Its course within the epicentral district (for which I am indebted to Mr. J. Horne, F.R.S.) is shown in Pl. XII and the text-figure on p. 392.

Several of the after-shocks were observed only at Dalarossie and a few other places in the valley of the Findhorn; and it is probable that they were due to movements along a fault in this district. The seismic evidence is insufficient to determine the position of this fault, except that it may run along the line of the valley. Mr. Horne informs me that the ground there has not yet been surveyed, but that he has proved the existence of faults along the Findhorn Valley near Drynachan Lodge, which lies about 11 miles down the valley from Dalarossie.

## III. FORE-SHOCKS.

The beginning of the series, which culminated in the earthquake of September 18th, seems to have occurred some time during the preceding summer months. No precise dates are available, but

<sup>1</sup> Phil. Mag. ser. 5, vol. 1 (1900) p. 51.

there is an isolated record of one in June at Aldourie, and of another in July at Dochgarroch. The first to attract general notice took place about thirty hours before the principal shock.

*a.* September 16th, 6.4 P.M.

Intensity, 4; epicentre, lat.  $57^{\circ} 24' 9''$  N., long.  $4^{\circ} 18' 5''$  W. Number of records 9, from 8 places (Pl. XII).

The disturbed area is roughly circular in form, about 12 miles in diameter, and contains about 108 square miles. Its centre lies about  $1\frac{1}{2}$  miles south of Dochgarroch, and three-quarters of a mile on the south-east side of the great fault. The shock was extremely slight, the vibrations being hardly perceptible, except at Dochgarroch. As a rule, the sound was also faint, though more prominent than the accompanying tremor. The approximate circularity of the disturbed area shows that the focus must have been small, an inference which is supported by the comparison of the sound with the discharge of cannon.<sup>1</sup>

September 17th, 11 P.M.: Inverness.—A quivering, lasting for 2 seconds.

September 18th, 1.15 A.M.: Dochgarroch.—A tremor, accompanied by sound.

IV. PRINCIPAL EARTHQUAKE.

*b.* September 18th, 1.24 A.M.

Intensity, 8; centre of Isoseismal 8, lat.  $57^{\circ} 26' 8''$  N., long.  $4^{\circ} 15' 8''$  W. Number of records 710, from 381 places; and 77 negative records from 68 places.

Time of occurrence.—For the time of occurrence stated above, I am indebted to Dr. Alexander Ross, F.G.S., of Inverness. It seems to me the most reliable of all the estimates, for it was observed immediately and checked by time-ball (Greenwich mean-time) during the following morning. It differs little, moreover, from the records given by several station-masters in the immediate neighbourhood of Inverness.<sup>2</sup>

Effects of the shock.—In Inverness, the damage to buildings, though never serious, was by no means inconsiderable. One brick building used as a smithy collapsed, several chimneys, or parts of them, fell, and many chimney-pots were displaced or overthrown.

<sup>1</sup> On September 16th, at 9.30 P.M., a slight shock is said to have been felt at Edderton, Fortrose, and Tain. No details are given, and the places of observation are so far one from the other and from the main epicentral area, that it is impossible to establish the seismic character of the disturbance, or even to regard it as probable.

<sup>2</sup> The Rev. A. Henderson informs me that the shock was registered by the Ewing seismograph in the Coats Observatory at Paisley, but the time given (1<sup>h</sup> 21<sup>m</sup> 35<sup>s</sup> A.M.) appears to me too early. The seismographs at the Ben-Nevis and Fort-William observatories and at the Royal Observatory, near Edinburgh, were not affected by the shock.

At Dochgarroch, and other places within the epicentral district, walls were cracked, chimneys thrown down, and lintels loosened.

But, for this country, the most remarkable effect of the earthquake was a long crack in the northern bank of the Caledonian Canal, near Dochgarroch Locks. It was formed in the middle of the towing-path, and could be traced at intervals for a distance of 200 yards to the east of the Locks and 400 yards to the west, being often a mere thread, and in no place more than half an inch wide. Shortly after the earthquake, heavy showers of rain obliterated the fissure; but Col. Mackinnon informs me, on the authority of the engineer in charge of the canal, that there can be no doubt whatever that the crack was caused by the earthquake.

**Epicentral area.**—The district within which slight damage to buildings occurred is bounded by the isoseismal 8, the innermost line in Pl. XI (shown on a larger scale by the dotted line in Pl. XII). The curve is 12 miles long, 7 miles wide, and contains 67 square miles: its longer axis running N.  $33^{\circ}$  E., and S.  $33^{\circ}$  W. The centre of the curve is about  $1\frac{1}{2}$  miles east-north-east of Dochgarroch, and three-quarters of a mile on the south-east side of the fault-line.

**Isoseismal lines and disturbed area.**—The isoseismal 8 is probably the only curve of the series that is accurately drawn throughout. In every other case, owing to the scarcity of observations in the West of Scotland, there are portions which must be regarded as doubtful.

Except towards the west, there are sufficient points to determine the course of the isoseismal 7. Its length is  $53\frac{1}{2}$  miles, width 35 miles, and area 1500 square miles; the longer axis is directed N.  $32^{\circ}$  E., and S.  $32^{\circ}$  W., and is therefore nearly parallel to that of the isoseismal 8. The distance between the isoseismals is 9 miles on the north-west side, and 14 miles on the south-east side.

Records of intensity 6 were difficult to obtain, as most observers slept in darkened rooms. As drawn on the map in the position which appears to me most probable (Pl. XI), it includes a district 105 miles long, 87 miles wide, and containing 7300 square miles. The distance between the isoseismals 7 and 6 is  $21\frac{1}{2}$  miles on the north-west, and 31 miles on the south-east side.

The path traced out for the isoseismal 5 is entitled to a greater degree of confidence. Its length is 157 miles, width 143 miles, and area about 17,000 square miles. The distance between the isoseismals 6 and 5 is  $21\frac{1}{2}$  miles on the north-west, and  $34\frac{1}{2}$  miles on the south-east side.

For the isoseismal 4, there are again but few determining points, and the curve could not have been drawn in the doubtful parts without reference to the preceding isoseismal. In the extreme North of Scotland, records come from Wick, Castletown, and other intermediate places. From the North-west of Sutherland and from Skye, observations are entirely wanting. The intensity was, however, equal to 4 at Tobermory, in the island of Mull. Towards the south, there are good accounts from Skelmorlie (in Ayrshire), Paisley,

Belsyde (near Linlithgow), Gullane (near North Berwick), and Dunbar. So far as I know, the earthquake was not felt in either Edinburgh or Glasgow, but the isoseismal 4 clearly passes to the south of the line joining these cities. The distance between the isoseismals 5 and 4 is 20 miles on the north-west, and 35 miles on the south-east side.

Isoseismal 4 may be regarded as the boundary of the disturbed area, for no observations seem to have been made outside it. The disturbed area is thus 215 miles long from north-east to south-west, 198 miles wide, and includes about 33,000 square miles.

Position of the originating fault.—Despite the somewhat doubtful character of the three outer isoseismals, the other two furnish abundant evidence for determining the position of the originating fault. The direction of their longer axes shows that the average direction of the fault must be N.  $33^{\circ}$  E., and S.  $33^{\circ}$  W. As the distance between the isoseismals is greater on the south-east than on the north-west side, we may infer that the hade of the fault is to the south-east. Again, the intensity of the shock being greater on the side towards which the fault hades, it follows that the fault-line must lie a short distance (about a mile or so) on the north-west side of the centre of the isoseismal 8.

The correspondence between the positions of the great boundary-fault and of the fault inferred from the seismic evidence, is so close that there can be little, if any, doubt that the earthquake was due to a slip along this fault. It will be seen that the evidence of the after-shocks offers additional support to this conclusion.

Nature of the shock.—Contrary to the general rule, there was little variation in the nature of the shock throughout the disturbed area. This will be seen from the following accounts, which are selected as typical from among those written by observers who were awake when the shock began:—

Inverness.—A gentle movement, followed by an extraordinary quivering, which increased in force for 2 or 3 seconds, and then decreased for 2 or 3 seconds; just as the quivering was about to cease, there was a distinct lurch or heave, after which the vibration was much more severe than before, and lasted several seconds longer than the first part of the shock.

Dalarossie.—The first indication was a loud sound, as of an express train coming from the east, rushing along close to, and then under, the northern wall of the house; this lasted for a few seconds, and towards the end of it the house vibrated. Then succeeded an interval of quietness for about one second, followed by a terrific burst or crash, not unlike the crash of a loud thunder-peal of about 2 seconds' duration, during which the house distinctly heaved up once and then sank back. After another brief interval of quietness, there was a low rumble, somewhat like the sound of a dying peal of thunder.

Aberlour.—A noise, like that of a traction-engine, was first heard, and at the same time a vibration was felt, such as is generally

associated with a traction-engine passing close at hand. Both noise and vibration ceased, and almost immediately there followed two or three heaves like a slight movement in a boat.

Aberdeen.—The shock consisted of two parts, the first a tremble, followed, after an interval of a few seconds, by a swinging movement of longer duration than the tremble.

Similar descriptions are given by observers in other parts of the disturbed area. If we divide the whole area into four quadrants by lines drawn through the epicentre parallel to the axes of the isoseismal 8, such records come, in the eastern quadrant, from Aberdeen, Aberlour, Dinnet, Duffus, Dyke, Forres, Huntly, Inverness, Monyruby, and Rothie-Norman: in the southern quadrant, from Aberfeldy, Blairgowrie, Dunbar, and Rothiemurchus: in the western quadrant, from Lochcarron: and along the line between the eastern and southern quadrants (that is, on the minor axis of the isoseismals), from Dalarossie and Montrose. Throughout the disturbed area, the shock thus consisted of two distinct parts, the second being of greater duration and intensity than the first, and consisting of vibrations of longer period. Near the epicentre there was no interval between the two parts; but, at a distance, the intermediate tremors were imperceptible, and the parts were separated by an interval of rest and quiet lasting 2 or 3 seconds.<sup>1</sup>

It follows that the two series of vibrations were produced by two distinct impulses, the stronger impulse succeeding the other after an interval of a few seconds. It is possible that the corresponding foci were nearly or quite detached, as in the twin earthquakes of Hereford in 1896 and Leicester in 1893; but it is more probable, I think, that the focus of the earlier impulse was overlapped by, or included within, that of the second.

Sound-phenomena.—Outside the isoseismal 5, there are but few records of the earthquake-sound; it was heard faintly, however, at Skelmorlie (in Ayrshire), Belsyde (near Linlithgow), and Gullane (near North Berwick). Towards the north, it was not observed beyond Wick and Watten (in Caithness). The extent of the sound-area must therefore have been about 27,000 square miles.

Throughout the whole disturbed area, 84 per cent. of the observers who describe the earthquake heard the accompanying sound. The percentage varies in different counties, from 93 in Inverness-shire to 77 in the counties of Perth and Aberdeen. In more distant regions, the records are too few to allow of the percentage of audibility being calculated; and the scarcity of observations in all but the south-eastern quadrant prevents, of course, the construction of isacoustic lines.

<sup>1</sup> According to 22 observers, who were awake when the earthquake began, there was only one series of vibrations, the places where they were situated being often close to those where the double series was observed. The duration of the shock is recorded by 13 of these observers, and their estimates give a mean duration of 2·8 seconds. As the average duration of the shock (according to 59 observers who were awake) was 4·7 seconds, it is therefore probable that these observers noticed only the second and more powerful series of vibrations.

The character of the sound is described by 394 observers; 39 per cent. of these compared it to passing waggons, traction-engines, etc., 25 per cent. to thunder, 14 to wind, 8 to loads of stones falling, 3 to the fall of heavy bodies, 4 to explosions or the firing of heavy guns, and 7 per cent. to miscellaneous sounds.<sup>1</sup>

There are the usual anomalies in the audibility and character of the sound, depending on the varying powers of the observers for hearing low sounds. This is especially noticeable in the case of the heavy crashes heard by some observers at the moment when the shock was strongest.

The variation in the sound throughout the sound-area was also normal. Its intensity gradually diminished outward from the epicentre, and most rapidly near the isoseismal 7, which bounds approximately the district in which the sound was very loud from that in which it was distinctly fainter. With one exception, the same curve includes all places at which the explosive crashes were heard with the strongest vibrations. Again, 34 per cent. of the observers within this line, and 44 per cent. of those outside it, compared the sound to passing vehicles, traction-engines, etc.; for thunder, the corresponding percentages are 34 and 18, for wind 8 and 19, for loads of stones falling 11 and 6, the fall of heavy bodies 2 and 4, explosions 7 and 3, and for miscellaneous sounds 5 and 5. Thus, with increasing distance from the centre, the sound became more uniform in character and intensity.

Time-relations of the sound and shock.—In the following table, the letters *p*, *c*, and *f* indicate the number of records per cent. in which any epoch of the sound preceded, coincided with, or followed, the corresponding epoch of the shock. In the last line, I have added the average percentages for three strong earthquakes: namely, the Pembroke earthquakes of 1892 and 1893, and the Hereford earthquake of 1896.

COUNTY.	Beginning.			Epoch of Maximum Intensity.			End.		
	<i>p</i>	<i>c</i>	<i>f</i>	<i>p</i>	<i>c</i>	<i>f</i>	<i>p</i>	<i>c</i>	<i>f</i>
Inverness .....	80	16	4	27	64	9	14	30	56
Ross .....	75	12	12	25	62	12	9	41	50
Nairn & Elgin .....	73	15	12	20	70	10	36	28	36
Banff .....	64	9	27	...	100	...	33	25	42
Aberdeen .....	19	67	14	...	100	...	...	60	40
Other counties .....	80	15	5	25	75	...	13	12	75
Whole sound-area .....	72	20	8	20	73	7	15	34	52
Average for strong shocks ...	78	14	8	25	67	8	20	23	57

<sup>1</sup> During the night of the earthquake, there was a strong wind in many parts of Scotland, which, however, generally subsided before the shock took place. Some of the observers may have mistaken a short gust for the earthquake-sound; but more than 60 per cent. of those who refer to this type record the time-relations of the sound and shock in such a manner as to leave no doubt on the subject.



Thus, as a general rule, the beginning of the sound preceded that of the shock, their epochs of maximum intensity coincided, while the end of the sound followed that of the shock. The most striking exception occurs in the case of Aberdeenshire, where, in the majority of cases, the three epochs coincided one with the other. This result is important in its bearing on the origin of the sound-vibrations, for most of the observations come from the south of the county, and the line joining this district to the epicentre is nearly perpendicular to the line of fault. Now, if the general precedence of the sound with respect to the shock were due to its superior velocity, the percentage of records in which the beginning of the sound preceded that of the shock would vary only with the distance, and not with the direction, from the origin. If, however, the sound-vibrations were to start simultaneously, or nearly so, from all parts of the focus, but especially from its marginal regions, then the three epochs of the sound and shock would coincide approximately at places near a line at right angles to the earthquake-fault. We may infer from the observed coincidence, and also from the fact that the sound generally followed the shock at distant stations, that the vibrations of every amplitude and period travelled outward with the same, or very nearly the same, velocity.

The time-relations of both terminal epochs are recorded by 180 observers, and from these we obtain the following table, in which are given the percentages of cases wherein the duration of the sound was greater than, equal to, or less than, that of the shock. The last line contains the corresponding average figures for the Pembroke earthquakes of 1892 and 1893, and the Hereford earthquake of 1896.

COUNTY.	GREATER.	EQUAL.	LESS.	DOUBTFUL.
Inverness .....	75	10	1	14
Ross .....	67	11	8	14
Aberdeen .....	6	75	...	19
Whole sound-area .....	60	14	3	23
Average for strong shocks .	57	18	5	20

Omitting doubtful records, we find that, in 78 per cent. of the cases, the duration of the sound was greater than, in 18 equal to, and in 4 per cent. less than, that of the shock. It is possible that the movements which produced the sound-vibrations lasted a longer time than those which produced the shock. But the more probable explanation is, that the area from which the sound-vibrations proceeded was larger than that whence the more prominent vibrations came, and extended beyond it at both ends; in other words, that the sounds heard before and after the shock came from the lateral margins of the focus.



## V. AFTER-SHOCKS.

In the following catalogue are supplied records of 46 shocks and 10 earth-sounds. Of these, 16 shocks and 1 earth-sound were noticed by several or many observers; the remainder depend on the evidence of one person alone. The list, however, is obviously far from being complete. Thus, on September 18th, between the two prominent after-shocks at 3.56 and 9 A.M., there is only one record given below; but Mr. D. Munro informs me that he felt 18 slight shocks at Dochgarroch within the same interval. Several shocks were also felt at Dores, and many earth-sounds were heard at Bunchrew, besides those contained in the register; while one observer at Lochend (Aldourie) estimates the total number of shocks up to October 23rd at about 70.

### c. September 18th, about 1.35 A.M.

Intensity, about 4; epicentre, lat.  $57^{\circ} 24' 9''$  N., long.  $4^{\circ} 16' 8''$  W. Number of records 7, from 7 places (Pl. XII).

The boundary of the disturbed area is uncertain towards the west. It is probably, however, nearly circular in form, as represented in Pl. XII, being  $10\frac{1}{2}$  or 11 miles in diameter, and containing about 88 square miles. Its centre is about  $1\frac{3}{4}$  miles south-east of Dochgarroch, and  $1\frac{1}{2}$  miles on the south-east side of the fault-line. The shock was very slight, and the sound a low rumble like distant thunder.

### d. September 18th, about 2 A.M.

Number of records 2, from 1 place.

A slight shock, accompanied by a noise like distant thunder, was felt at Glenmazeran, near Dalarossie, in the valley of the Findhorn.

### e. September 18th, about 2.30 A.M.

Number of records 2, from 2 places.

A slight tremor was felt at Inverness and Abersky, and at the latter place was accompanied by a noise like that of a passing vehicle.

### f. September 18th, about 3 A.M.

Number of records 2, from 2 places.

A tremor only was observed by the engineer at the Inverness District Asylum (2 miles west-south-west of Inverness), and a slight rumbling at Aigas (near Beauly).

### g. September 18th, 3.56 A.M.

Intensity, not less than 5; centre of isoseismal 5, lat.  $57^{\circ} 25' 3''$  N., long.  $4^{\circ} 15' 9''$  W. Number of records 90, from 43 places; also 6 doubtful records from 5 other places (Pl. XII).

This was clearly the strongest of the whole series of after-shocks, though it exceeded but slightly the shock felt twelve days later

(September 30th). The records are comparatively numerous, but many amount to little more than a statement that the shock was felt; and it is impossible to draw the isoseismal lines with any approach to accuracy. On the map (Pl. XII) the isoseismal 5 alone is shown, and even the course of this must be regarded as doubtful. Its length, as drawn, is 38 miles, width 25 miles, and the contained area about 750 square miles. The centre is situated 2 miles east-south-east of Dochgarroch, and 1·7 miles on the south-east side of the fault, and the longer axis is roughly parallel to the fault-line.

Outside this isoseismal, the shock was felt at Little Scatwell, Relugas, Dunphail, and Grantown, which are respectively 18, 24, 25, and 26 miles from the centre of the isoseismal 5. There are also records of its occurrence at Deskford, Ordiquhill, and Banff, places near to one another, and respectively 57, 59, and 67 miles from the centre; and at Comrie and Crieff, distant 73 and 76 miles. The absence of observations at intermediate localities makes these records somewhat doubtful, but there is nothing impossible in an after-shock of this intensity being felt so far from the epicentre.

The shock consisted of two or three distinct oscillations, the average of seven estimates of its duration being  $2\frac{1}{2}$  seconds. At Dochgarroch and Inverness, and in the immediate neighbourhood, these vibrations seemed to be nearly vertical.

The sound was certainly heard by 62 per cent. of the observers. It was compared to passing waggons, etc. by 14 per cent. of those who described it, to thunder by 43 per cent., wind by 14, the fall of a heavy body by 7, explosions by 14, and to miscellaneous sounds by 7 per cent. The beginning of the sound preceded that of the shock in 62 per cent. of the records, coincided with it in 25, and followed it in 12 per cent. The end of the sound coincided with that of the shock in 17 per cent., and followed it in 83 per cent., of the records. The duration of the sound was generally greater, and never less, than that of the shock.

The direction of the longer axis of the curve and the position of the centre favour the connection of this earthquake with the boundary-fault. Moreover, the sound was heard at two places—Garve and Little Scatwell—on the north-west side of the isoseismal 5, and respectively distant 7 and 6 miles from it. As the sound-vibrations from the upper margin of the focus would be more readily heard than those from the lower margin, this fact confirms the inference that the hade of the earthquake-fault must be to the south-east.

September 18th, about 6.25 A.M.: Inverness.—A noise was heard, but much slighter than that which accompanied the shock at 3.56 A.M.

#### *h. September 18th, 9 A.M.*

Intensity, 5; epicentre, lat.  $57^{\circ} 27' 0''$  N., long.  $4^{\circ} 15' 1''$  W. Number of records 26, from 18 places (Pl. XII).

The disturbed area of this shock is elliptical in form, and is

25 miles long,  $12\frac{1}{2}$  miles wide, and 250 square miles in area. Its longer axis runs N.  $36^{\circ}$  E., and S.  $36^{\circ}$  W., and the centre is situated 2 miles east-north-east of Dochgarroch, and 1 mile to the south-east of the fault.

The shock consisted of a single series of vibrations, and was accompanied by a sound which is variously described as resembling a passing vehicle, thunder, or the discharge of cannon.

September 18th, 12 (noon): Inverness District Asylum.—A mere tremor, but strong enough to knock down some loose plaster which was lying on the joists of buildings.

September 18th, about 11.25 P.M.: Inverness.—A low, but distinct, rumble.

September 20th, 4 P.M.: Does.—A slight shock.

September 21st, 10.45 A.M.: Holm (near Lentrán).—A shock, direction west to east, accompanied by a noise like the discharge of cannon.

September 21st, 11.20 A.M.: Holm.—The same.

September 21st, 3.15 P.M.: Holm.—The same.

#### *i.* September 23rd, about 7.30 A.M.

Number of records 4, from 4 places.

The only records of this earthquake come from Does, Holm, the Inverness District Asylum, and Kirkhill. The shock was very slight, of intensity probably less than 4. At Does the sound resembled the rumbling of a coach, and at Holm the discharge of cannon. The epicentre lay probably in the neighbourhood of Dochgarroch.

September 22nd, 9 A.M.: Teanassie (near Beaulieu).—A shock felt and rumbling noise heard, the latter being the more noticeable.

September 24th, 5.15 A.M.: Holm.—A shock, the direction of which was from west to east, accompanied by a sound like the discharge of cannon.

September 24th, 7.10 A.M.: Holm.—The same.

September 24th, 4.20 P.M.: Holm.—The same.

September 26th, 8.8 A.M.: Holm.—The same.

September 26th, 9.25 A.M.: Holm.—The same.

#### *j.* September 26th, 11.40 A.M.

Intensity, 4. Number of records 3, from 3 places.

The shock was felt at Does and Holm. At Drumälan (near Drumnadrochit) there was no tremor, and the sound was like that of a train gradually approaching, passing, and receding from the house.

September 26th, 9.39 P.M.: Holm.—A shock, of intensity less than 4, accompanied by a sound like that of distant cannon.

*k.* September 27th, 1.47 P.M.

Intensity, 5. Number of records 2, from 2 places.

The intensity of this shock was 5 at Holm, and probably 4 at Aigas (6 miles south-west of Beaulieu). The sound was heard at both places, and at Holm resembled that of distant cannon. Considering the intensity of the shock, it is remarkable that no more records are forthcoming; but there is no reason to doubt its genuineness.

*l.* September 28th, about 4 A.M.

Intensity, 5. Number of records 2, from 1 place.

A slight shock noticed in Inverness. There is no record of any sound.

September 28th, 11.50 A.M.: Glen Urquhart.—The exact position of the place of observation is uncertain, but it is probably near Loch Ness. Both shock and sound were extremely slight, the intensity of the former being less than 4.

September 28th, 1.40 P.M.: Loch Ness.—The observer of the preceding shock was in a boat on Loch Ness at 1.40 P.M. The boat moved distinctly, and a slight tremor was felt.

September 29th, about 4.30 A.M.: Inverness.—A slight shock, accompanied by a faint sound like distant thunder.

*m.* September 29th, 9.6 P.M.

Intensity, 4; epicentre, lat.  $57^{\circ} 26' 1''$  N., long.  $4^{\circ} 17' 0''$  W. Number of records 6, from 5 places (Pl. XII).

The places where this earthquake was observed lie within an area which is probably circular in form, about  $8\frac{1}{2}$  miles in diameter, and including about 57 square miles. The centre is nearly 1 mile east of Dochgarroch and three-fifths of a mile south-east of the fault. (At 9.10 P.M. a sound, as of a carriage passing, with scarcely any accompanying tremor, was heard at Bridgend, 3 miles from Dalarossie and about 13 miles from the epicentre.) The shock was slight, and the sound faint and of brief duration, leading, in conjunction with the approximate circularity of the disturbed area, to the inference that the focus was very small.

September 29th, 11 P.M.: Aigas.—A rumbling sound heard.

September 29th–30th: Drumälan (Drumnadrochit).—During the night, two slight shocks were felt before the shock of September 30th, 3.39 A.M., by observers who were awake. One of these may be identical with the sound heard at Aigas at 11 P.M. on September 29th.

*n.* September 30th, 3.39 A.M.

Intensity, 7; epicentre, lat.  $57^{\circ} 24' 5''$  N., long.  $4^{\circ} 19' 3''$  W. Number of records 54, from 33 places (Pl. XII).

On the map (Pl. XII) are shown the isoseismal 5, part of the

isoseismal 6, and the isoseismal 7 approximately. Outside the isoseismal 5, records of the shock are scanty; but the intensity was 4 as far as Lochluichart, which is 22 miles north-west of the epicentre and 13 miles from the isoseismal 5. A shock was also reported at about 4 A.M. from Crathes (Kincardineshire); but, as that locality is 74 miles from the epicentre, the connection between this disturbance and the earthquake under consideration is doubtful.

The isoseismal 7, which is only roughly drawn, is 5 miles long,  $2\frac{1}{2}$  miles wide, and contains about 10 square miles. Its centre is 2 miles south-by-west from Dochgarroch, and half a mile on the south-east side of the fault. The isoseismal 5 is 33 miles long, 23 miles wide, and 595 square miles in area: its longer axis running N.  $34^{\circ}$  E. and S.  $34^{\circ}$  W. The distance between the isoseismals 7 and 5 is 8 miles on the north-west, and  $12\frac{1}{2}$  miles on the south-east side. The originating fault must therefore run N.  $34^{\circ}$  E. and S.  $34^{\circ}$  W., and must have trended to the south-east. The closeness of the epicentre to the line of fault shows that the depth of the seismic focus must have been very small; and the rapid decrease in the intensity of the vibrations as they radiated outward points to the same conclusion.

The shock, the mean duration of which was 3 seconds, differed in one respect from those that preceded it. The movement at Inchmore (Kirkhill) was distinctly more lateral, more undulating or swinging, than in the others. At Inverness one observer remarks that the movement was horizontal, as distinguished from the vertical or 'choppy-sea' motion of the principal shock.

The sound was heard by at least 80 per cent. of the observers. It was compared to passing waggons etc. in 25 per cent. of the records, to thunder in 50 per cent., wind in 4, loads of stones falling in 4, explosions in 8, and miscellaneous sounds in 8 per cent. The beginning of the sound preceded that of the shock in 61 per cent. and coincided with it in 39 per cent. of the records; while the end of the sound preceded that of the shock in 16 per cent. of the records, coincided with it in 28, and followed it in 56 per cent. The duration of the sound was greater than that of the shock in 64 per cent. of those records in which the time-relations of both terminal epochs are given, was equal to it in 18 per cent., while in the remaining 18 per cent. the relative duration of the sound and shock is doubtful.

September 30th, about 4.10 A.M.: Aldourie.—A slight shock.

*o.* October 1st, about 4.35 A.M.

Intensity, 5. Number of records 2, from 2 places.

A shock, preceded, accompanied, and followed by a sound like thunder, was felt at Dalarossie and Coignafuinternach.

October 1st, about 3 P.M.: Dalarossie.—A faint sound, like distant thunder, was heard, without any shock.

Q. J. G. S. No. 231.

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October 1st, 5.6 P.M. : Holm.—A shock of intensity less than 4, accompanied by a sound as of distant thunder.

October 2nd, 2.7 P.M. : Holm.—The same.

*p.* October 6th, 4.24 A.M.

Intensity, 5. Number of records 2, from 2 places.

At Dochgarroch two vibrations were felt (intensity 5), without any sound. The shock was also felt at Holm. It is probable that the epicentre was not far from Dochgarroch, and that the depth of the focus was small.

October 9th, 7.40 P.M. : Dalarossie.—A shock (intensity probably 5), preceded, accompanied, and followed by a sound like that of a light carriage passing.

October 12th, 8.40 A.M. : Dochgarroch.—A single vibration (intensity 5), accompanied by a rumbling sound.

October 12th, 12.56 P.M. : Holm.—A slight shock.

October 12th, about 4 P.M. : Inverness.—A shock, as if a heavy body fell against the house and was then dragged along the side of it.

October 13th, 12.30 P.M. : Dalarossie.—A slight sound, without any tremor.

*q.* October 13th, 4.24 P.M.

Intensity, probably 4; epicentre, lat.  $57^{\circ} 26' 1''$  N., long.  $4^{\circ} 18' 0''$  W. Number of records 7, from 5 places (Pl. XII).

The records are too few to determine the boundary of the disturbed area; but it is clearly elliptical in form, with its axis approximately parallel to those of the isoseismal lines of previous shocks. The length of the curve, as drawn (Pl. XII), is 8 miles, the width  $5\frac{1}{2}$  miles, and the area contained by it about 35 square miles. The centre is about a quarter of a mile south-east of Dochgarroch, and a tenth of a mile from the fault-line. The shock consisted of two or three vibrations, and was accompanied by a loud report, compared by an observer near Dochgarroch to a shot from a gun, followed by a sound as of the ball passing through the air. At Muirtown, which is near Inverness and close to the line of fault, the sound resembled that of a heavy vehicle approaching. The focus was about 2 miles in length, and lay at a very small depth.

October 13th, about 5.30 P.M. : Holm.—A very distinct shock.

October 14th, 1 A.M. : Inverness.—A shake, preceded by a sound like the sighing of the wind through trees.

October 14th, 5 P.M. : Dochgarroch Locks.—A shock (intensity less than 4), accompanied by a sound like that of a heavily-loaded lorry running on a country-road.

October 22nd, 5.30 A.M. : Drumnadrochit.—A distinct tremor.

*r.* October 22nd, about 10.15 A.M.

Number of records 2, from 2 places.

The only records of this earthquake come from Aldourie and Drumnadrochit. At Aldourie, eight or nine sounds were heard between 9.45 A.M. and noon. The sound here at about 10.15 A.M. was very distinct, and resembled the roar of a furnace when the door is open, or of an underground train; it lasted 2 or 3 seconds, and seemed to travel eastward. No distinct shock was felt, but there was evidently a very weak tremor. At Drumnadrochit only a sound was heard, like distant thunder, growing louder and dying away. The focus lay probably beneath Loch Ness.

October 22nd, 12.55 P.M.: Drumnadrochit.—A sound, like distant thunder, without any accompanying tremor.

October 22nd, 8.20 P.M.: Bunchrew.—A slight tremor, accompanied by a rumbling sound.

October 22nd, 8.25 P.M.: Bunchrew.—A rumbling sound.

November 5th, 12.12 A.M.: Dalarossie.—A rumbling sound, like thunder, not loud, lasting about 4 or 5 seconds, without any sensible shock.

*s.* November 15th, about noon.

An underground rumbling sound was heard by several persons at Dochgarroch.

November 15th: near the end of Loch Ness.—An underground rumbling sound was heard during the night.

November 21st: Dochgarroch.—A slight vibration and rumbling sound were observed during the night.

Sound-Phenomena of the After-Shocks.

Many accounts of the after-shocks are little more than mere records of their occurrence. If we exclude these, the percentage of audibility of all the after-shocks is 77. That of the shock of September 18th, 3.56 A.M., is 62; and of the shock of September 30th, 80. Omitting these shocks, the percentage is 85, showing that the sound, though much fainter than that which accompanied the principal earthquake, was nevertheless a comparatively important feature.

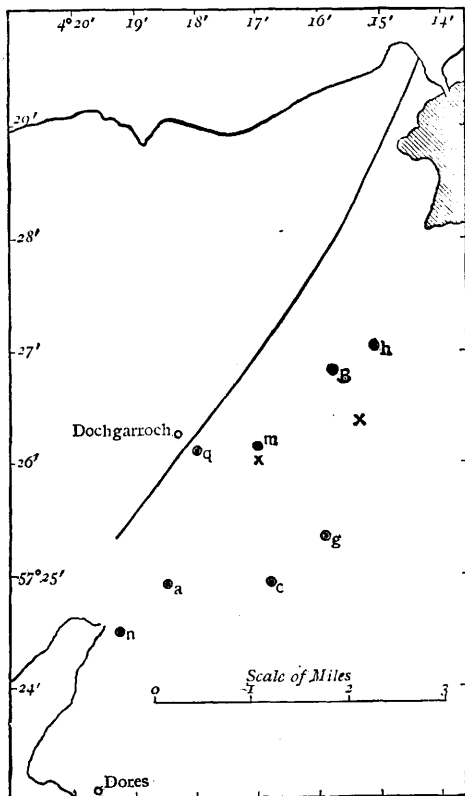
Taking all the after-shocks together, the comparisons of the sound to passing waggons, etc., occur in 26 per cent. of the records, to thunder in 43, wind in 7, loads of stones falling in 2, the fall of a heavy body in 2, explosions, etc., in 17, and miscellaneous sounds in 3 per cent. Omitting the two strongest after-shocks on September 18th and 30th, the corresponding figures are: passing waggons, etc. 33, thunder 33, wind 5, and explosions 28. These are about the proportions met with in slight earthquakes, and indicate that, as a rule, the foci of the after-shocks were of small linear dimensions.



## VI. ORIGIN OF THE EARTHQUAKES.

In the absence of a definite fault-scarp,<sup>1</sup> it would be difficult to obtain clearer evidence than that given above of the connection between several of the Inverness earthquakes and the great

*Centres of the epicentral areas of the Inverness earthquakes.*



- a = Fore-shock a (p. 379).
- B = Principal earthquake (p. 379).
- c = After-shock c (p. 385).
- g = After-shock g (p. 385).
- h = After-shock h (p. 386).
- m = After-shock m (p. 388).
- n = After-shock n (p. 388).
- q = After-shock q (p. 390).

boundary-fault. The axes of the iso-seismal lines are parallel to the mean direction of the fault; the epicentres, or the centres of the inner isoseismals (see text-figure) lie a short distance to the south-east of the fault, that is, on the side to which the fault fades; and most of them lie within a band which is nearly parallel to the fault-line and the centre of which is less than a mile south-east of Dochgarroch.

The dots in the figure mark only the centres of the epicentral areas. In many earthquakes, the focus was no doubt small (possibly less than a mile in length); but in the principal earthquake and in the after-shocks of September 18th, 3.56 and 9 A.M., and September 30th, 3.39 A.M. (denoted by the letters g, h, and n), its length must have amounted to several miles.

<sup>1</sup> The absence of a fault-scarp is sometimes felt as an objection to the fault-slip theory; but, when the slip within the focal area is small (perhaps, in this case, only a fraction of an inch), it would die out before reaching the surface.

Earthquakes of 1890.—The last strong earthquake in the Inverness district occurred on November 15th, 1890.<sup>1</sup> It seems to have been preceded by several slight earth-sounds, and was followed by not less than ten after-shocks, the series ending on December 14th. The epicentre of the principal earthquake was situated in lat.  $57^{\circ} 25' 0''$  N., long.  $4^{\circ} 10' 8''$  W., or  $4\frac{1}{2}$  miles S.  $21^{\circ}$  E. of Inverness, and  $4\frac{1}{3}$  miles from the fault-line. As the longer axes of the isoseismal lines ran from N.  $48^{\circ}$  E. to S.  $48^{\circ}$  W., it seemed to me probable that this shock was caused by a slip along a fault passing through a point about 1 mile south-east of Daviot, inclined at an angle of  $13^{\circ}$  to the boundary-fault, and hading to the north-west. I have re-examined the evidence on which this conclusion was founded; and, though I am unable to interpret it otherwise, I think it possible that a larger series of records might have led to a different result.

The epicentre of this earthquake lies outside the area represented in the map on p. 392; but a line drawn through it at right angles to the fault-line would pass very nearly through the centre of the principal earthquake of 1901. The small crosses ( $\times$ ) mark the epicentres of two of the after-shocks in 1890, those of November 15th, 6.15 P.M., and December 14th, 3.30 A.M.: the latter being quite close to the epicentres of two after-shocks ( $m$  and  $q$ ) of the recent series.<sup>2</sup> If the principal earthquake were due to a slip along the boundary-fault, there is thus an evident displacement of the focus in subsequent shocks towards the south-west.

Fore-shocks of 1901.—Between December 14th, 1890, and the summer of 1901, no earthquakes, so far as I am aware, were felt in the Inverness district. The stresses tending to produce slipping were clearly increasing along the whole portion of the fault between Loch Ness and the sea. Here and there, however, were certain small areas of the fault-surface in which the resistance to slipping was greater than elsewhere; and this resistance had to be overcome before any general movement could take place. One of these areas was situated about half a mile north-east of the end of Loch Ness, and the slip here gave rise to the first shock which attracted general observation. Two others, if we may rely on solitary records, existed farther to the north-east, where the resistance gave way within three hours of the occurrence of the principal shock.

Principal earthquake of 1901.—The removal of these small obstructions helped to equalize the effective stress along several miles of the fault; so that the next displacement, which resulted in the principal shock, took place over a region extending

<sup>1</sup> Quart. Journ. Geol. Soc. vol. xlvii (1891) pp. 618-32.

<sup>2</sup> The epicentre of another shock of the 1890 series (November 16th, 8.30 P.M.) lies about half a mile west of Dochgarroch. This point is on the north-west side of the fault, and may be incorrectly determined owing to the scantiness of the evidence.

nearly from Loch Ness to Inverness. There were two distinct slips in rapid succession, with continuous slight motion between them, the second being greater in amount and extending over an area which probably overlapped, even if it did not entirely include, that within which the first took place.

After-shocks of 1901.—The immediate result of this displacement was a change of stress over a great extent of the fault-surface—a decrease, for the most part, near the centre of the principal focus, and an increase within and near its marginal regions. In places, the augmented stress produced secondary slips, each of which resulted in further changes of stress, and as a rule in decreasing slips, until the stresses were everywhere reduced below the maximum resistance capable of being offered to movement.

The sequence of events is rendered clearer if, for the present, we disregard the very small slips (some of which may have been due to merely local variations of stress), and confine our attention to the six chief after-slips, three of which were of much greater importance than the rest, and affected several miles of the fault-surface.

An interval of only 10 minutes separated the principal earthquake and its first successor. This was caused by a small slip (*c*, p. 385) near the south-western margin of the principal focus. After  $2\frac{1}{4}$  hours, the chief after-slip (*g*, p. 385) occurred; its centre migrated about half a mile to the north-east, but, as the focus was several miles in length, its south-western margin extended some distance beyond that of the principal focus. The seat of action was then transferred to the other side of that focus, a long slip (*h*, p. 386) taking place after the lapse of about 5 hours; its centre was approximately half a mile north-east of the principal centre, and its focus probably extended a little beyond the north-eastern margin of the principal focus. During the next  $11\frac{1}{2}$  days there were no important movements; but at the end of that time a small slip (*m*, p. 388) occurred about 1 mile to the south-west of the principal centre, and close to Dochgarroch. This was followed, in  $6\frac{1}{2}$  hours, by the third long after-slip (*n*, p. 388), the centre of which lay to the south-west of the principal focus, and the slip itself must have extended 2 or 3 miles beneath Loch Ness. Again, after a further lapse of  $13\frac{1}{2}$  days, there was a slip (*q*, p. 390), about 2 miles long, in the immediate neighbourhood of Dochgarroch.

Thus, of the six chief after-shocks, one originated within the region of the fault lying to the north-east of the principal centre, and the rest within that to the south-west.

There remain eleven after-shocks recorded by more than one observer. Two of these had no connection with the boundary-fault; the epicentres of four are undetermined; of the others, the focus of one lay to the north-east, and the foci of four to the south-west, of the principal centre.

Further light is thrown on the nature of the fault-movements

by the numerous tremors and earth-sounds recorded by single observers<sup>1</sup>; for, in such slight disturbances, the epicentres must have been close to the places of observation. The numbers recorded in different districts near the boundary-fault are as follows:—

Inverness and Bunchrew .....	8
Dochgarroch and Holm .....	16
Dores, Aldourie, etc. ....	3
Drumnadrochit, etc. ....	6

Thus, 8 probably originated on the north-east side of the principal centre, and 25 on the south-west side.

To sum up. The great slip, which caused the principal shock, reached nearly from Loch Ness to Inverness, and was greatest at a point about halfway between. The three chief after-slips resulted in an extension of this area of principal displacement in both directions along the fault-surface, the extension towards the north-east being small (probably less than half a mile), while that towards the south-west amounted to 6 miles or more. The smaller after-slips (some of them mere creeps) were most numerous in three regions—one lying about a mile south-west of the principal centre, the others near Inverness and Drumnadrochit, which lie near the extremities of the displaced area of the fault, while in the intermediate regions they were apparently less frequent.

In addition to the migration of the focus in the direction of the fault, there was also, in the six principal after-shocks, a continuous decrease in the depth of the focus, for the distances of the epicentres of these shocks from the fault-line are respectively 1·5, 1·7,<sup>2</sup> 1·0, 0·6, 0·5, and 0·1 mile.<sup>3</sup>

Sympathetic earthquakes.—In the list of after-shocks, there are records of six shocks or earth-sounds observed only in the valley of the Findhorn, which lies 13 or 14 miles to the south-east of the boundary-fault. The times at which they occurred are: September 18th, about 2 A.M.; October 1st, about 4.35 A.M. and 3 P.M.; October 9th, 7.40 P.M.; October 13th, 12.30 P.M.; and November 5th, 12.12 A.M.: the first two shocks being recorded by more than one observer. As one of these shocks was of intensity 5,

<sup>1</sup> It should be remembered that some of these may not have been of seismic origin.

<sup>2</sup> In this case (*g*) the distance refers to the centre of the isoseismal 5, which would be somewhat farther to the south-east than the true epicentre.

<sup>3</sup> It is interesting to notice that similar laws governed the distribution of the after-shocks of the great Japanese earthquake of 1891. In that case, the area of displacement was 70 miles or more in length, and the after-slips affected for the most part a nearly central region (in which they were exceedingly numerous), and two more or less isolated districts near or surrounding the extremities of the fault. After the lapse of some months, the latter districts became practically inactive, and there was a gradual but oscillating withdrawal of the after-slips to a more or less central district; while, at the same time, the depth at which the slips occurred continually diminished. See *Quart. Journ. Geol. Soc.* vol. liii (1897) pp. 1-15 & *Geogr. Journ.* vol. xvii (1901) pp. 635-55.

and another not much, if at all, weaker, it is clear that, if they had been due to slips along the boundary-fault, they could not have escaped notice by one or more of the watchful observers at Dochgarroch, Dores, Drumnadrochit, Holm, and Inverness. They must therefore have been of local origin. Mr. S. Archibald, to whose careful observations and enquiries we are indebted for the knowledge of these after-shocks, informs me that he has on several previous occasions heard mysterious rumbling noises at Dalarossie; but the occurrence of the recent shocks and sounds in such close succession to the principal Inverness earthquake shows, I think, that the great slip on September 18th was responsible for the precipitation of the movements in the Findhorn Valley.<sup>1</sup>

Conclusion.—The region which lies between Loch Ness and the sea appears to be in a stage of more rapid development than any other in the British Islands. In all probability, the earthquakes of 1816, 1888, and 1890 originated within it, as well as many of the minor shocks that followed them. That the earthquake of August 13th, 1816, was the strongest of the series is evident from the damage which it caused to buildings in Inverness and from the large area that it disturbed. Its series of after-shocks, of which no doubt only the more important were recorded, lasted until November 10th, 1818; and it is worthy of notice that, so far as we can judge from the scanty materials that have come down to us, the foci of some of these after-shocks lay beneath the north-eastern end of Loch Ness. The earthquake of February 2nd, 1888, was probably also attended by a train of after-shocks; but no accounts of them seem to have been published. After the earthquake of November 15th, 1890, the foci of the minor shocks showed a tendency, though with some oscillations, to recede in a south-westerly direction towards Loch Ness; while in 1901 this tendency, as we have seen, was revealed in a very striking manner.

The earthquakes provide no evidence with regard to the direction of the displacement along the boundary-fault; they do not tell us whether the rock on the south-east side of the fault was elevated or depressed with reference to that on the north-west side. There can be little doubt, however, that Loch Ness is still growing; but, without instrumental observations continued for many years, it can hardly be decided whether the lake is now contracting in area, or whether it is gradually, though very slowly, pushing its way outward to the sea.

<sup>1</sup> The shock and sounds observed at Teanassie on September 22nd, and Aigas on September 29th, may have had a similar origin. These places are both 8 miles to the north-west of the boundary-fault.

Immediately after the Japanese earthquake of 1891, there was a great and sudden increase of seismic activity in two detached regions, one 45 miles north-east, and the other 55 miles south-west of the meizoseismal area. See *Geol. Mag.* 1897, pp. 23–27 & *Geogr. Journ.* vol. xvii (1901) p. 653.

EXPLANATION OF PLATES XI & XII.

PLATE XI.

Map showing the isoseismals 4, 5, 6, 7, & 8 of the principal Inverness earthquake, on the scale of 30 miles to the inch.

PLATE XII.

Map illustrating the area affected by the accessory shocks of the Inverness earthquake, on the scale of 6 miles to the inch.

DISCUSSION (ON THE TWO FOREGOING PAPERS).

Prof. JUDD said that everyone must be struck by the conjunction of two earthquakes with such dissimilar features. The movement in Cumberland was probably not of long continuance nor originating from a very old disturbance; moreover, it seemed to take place along a fault of which there was no evidence at the surface. In the Loch-Ness district, however, the fault-line was plainly apparent at the surface, and there was evidence that the recent disturbance was the continuation of movements that have been going on for ages. He expressed his gratitude to the Author for the care that he had taken in bringing the facts together.

The Rev. EDWIN HILL expressed admiration of the Author's work. Referring to the Carlisle paper, he asked whether the words 'in the surface-rocks there is no sign' of such a fault, meant that these rocks were not faulted. If so, did this imply that stress had been accumulating through geological periods, or that a cause of stress had after such periods been renewed? The latter was easier to imagine. He had heard that a recent earthquake in New Zealand had been followed by frequent movements through many weeks, and expressed a hope that there had been some working on the spot as enthusiastic as the Author.

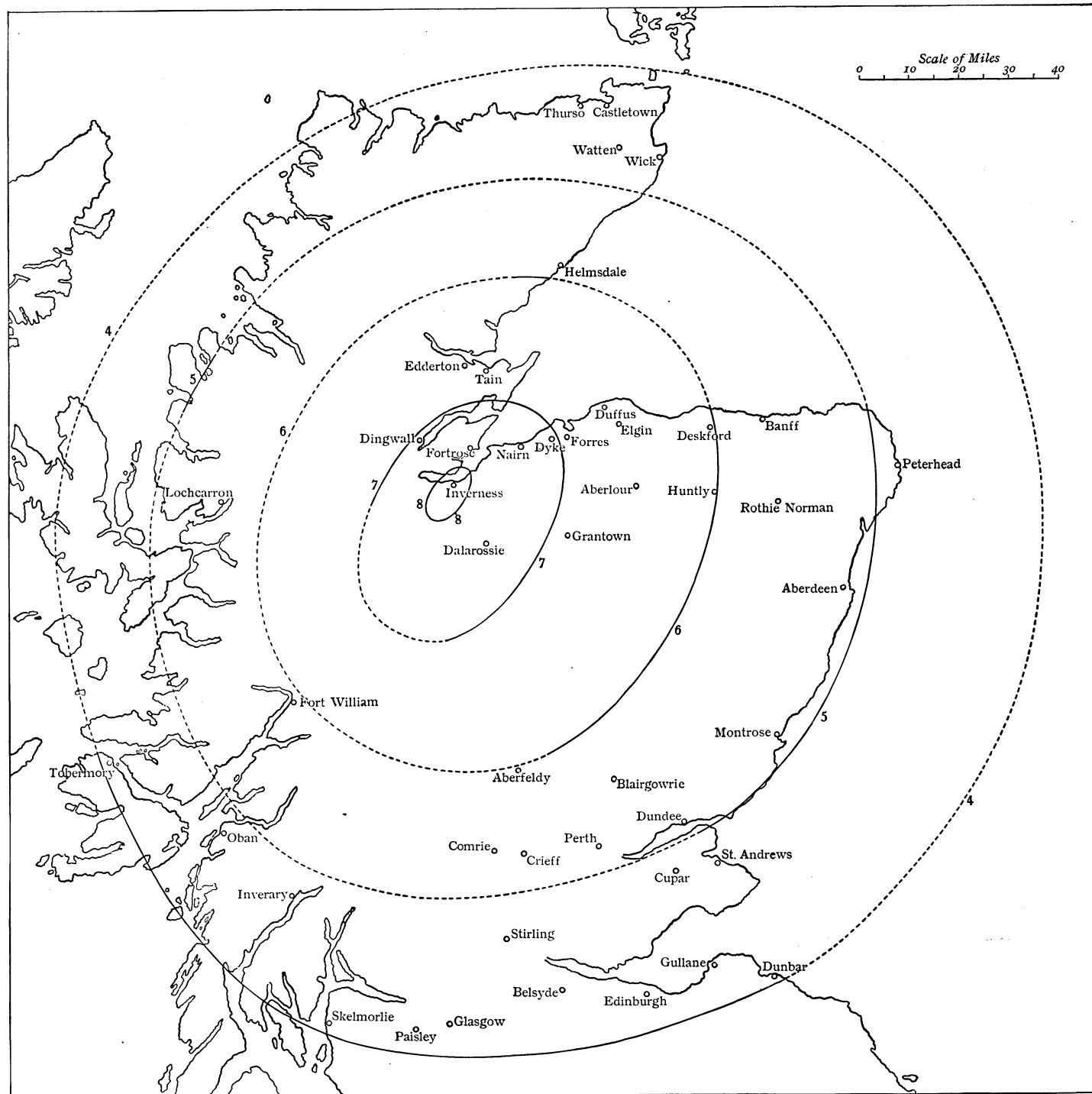
Mr. GIBSON cited instances from North Staffordshire and Nottinghamshire of great faults affecting the Coal-Measures, now buried beneath the undisturbed Trias. Such faults might be revealed by earthquakes.

The PRESIDENT referred to the great geological importance of the Author's researches into the phenomena and distribution of British earthquakes in general; and pointed out how greatly he had enlarged our previous ideas as to their frequency in what we very naturally regard as a comparatively stable region. The painstaking manner in which he collected his materials, and the cautious way in which he drew his conclusions, inspired one with confidence in his results. He was especially to be congratulated on the advance that he had made in our knowledge of the subject as a whole, by his demonstration that most, if not all, the British earthquakes are due to slipping movements along fault-planes; by the discovery of twin earthquakes, and of the fact that the trends of the various earthquake-sliplines are more or less coincident with the four recognizable trends of crust-folding in the

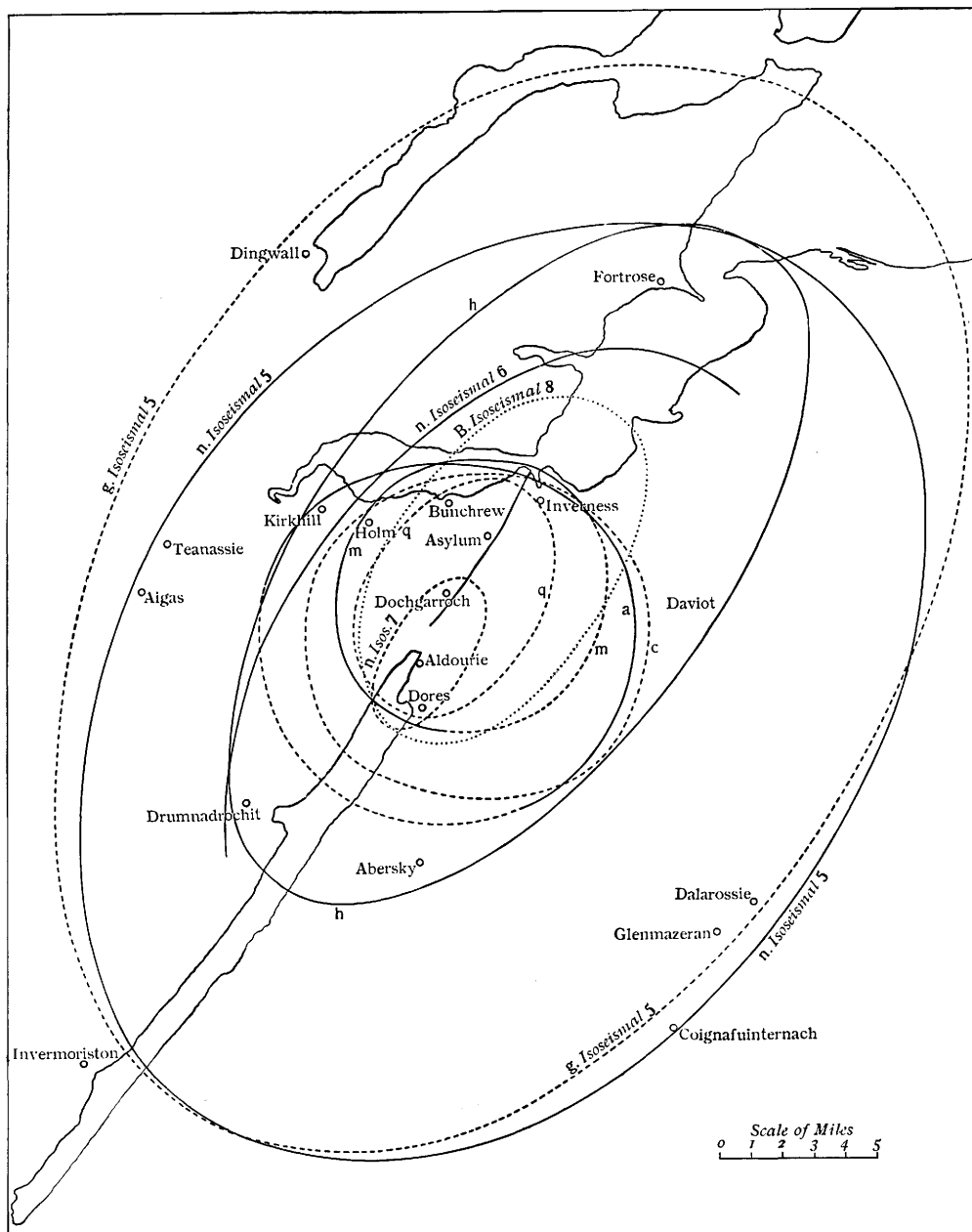
country. The Carlisle earthquake appeared exceptional, at first sight, in the fact that the direction of the presumed deep-seated fault-line ran almost meridionally, or from north to south, instead of diagonally, or from north-east to south-west, which is the strike of the deep-seated rocks of the Lake District. But it behoved us to remember that this meridional or Malvernian trend is practically that of the neighbouring Pennine Chain as a whole, and of the typical portion of its great Craven Fault.

In regard to the Inverness earthquakes, it was most significant to notice that where, as in this case, the fault-plane is of very great length, the earthquake-movement is of proportionate magnitude. While the oscillation-earthquakes along the fault-line itself might be due to the gradual and intermittent adjustment of the parts upon the opposite walls of the fault-fissure, it was not unlikely that the sympathetic earthquakes of the Findhorn, etc. might be owing to those broader areas of the earth-crust which extend for many miles from the fault-plane also slowly settling down into equilibrium with the new conditions of crust-strain brought about by the main earthquake. As respects the view that Loch Ness was still growing, the Author's idea seemed to be in harmony with the speaker's own suggestion made many years since, that the Loch-Ness depression in general is an 'intermont valley' the sides of which are gradually approximating because of crust-creep. If so, the lake is deepening, but not necessarily increasing proportionately in length.





# MAP ILLUSTRATING THE AREA AFFECTED BY THE ACCESSORY SHOCKS OF THE INVERNESS EARTHQUAKE.



a = Fore-shock *a* (p. 379).

c = After-shock *c* (p. 385).

g = After-shock *g* (p. 385).

h = After-shock *h* (p. 386).

m = After-shock *m* (p. 388).

n = After-shock *n* (p. 388).

q = After-shock *q* (p. 390).