PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Royal Society Expedition to Montserrat, B.W.I. Final Report

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THE ROYAL SOCIETY EXPEDITION TO MONTSERRAT, B.W.I.

FINAL REPORT

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[Plates 1–5]

1—Introduction

In a previous paper (Powell 1937) an account has been given of the results obtained in Montserrat, from 24 March to 24 July 1936, with the physical apparatus installed in the island by members of the Royal Society Expedition. The present paper gives a more detailed account of the methods employed and the results obtained up to 8 July 1937 with the instruments maintained in the island, together with the conclusions which have followed from a more complete examination of the records. In addition, based on the experience gained during the course of the expedition, recommendations are made as to the most suitable type of instruments for the investigation of the particular kind of seismic phenomena which have occurred in Montserrat during the past 3 years.

The principal object of the expedition was to obtain observations which would serve as a basis of comparison in the event of any serious changes taking place in the island. For this purpose it was desirable to make as many empirical observations as possible with the equipment which was provided. In the course of the work a number of problems have arisen, and tentative solutions to them have been given in the paper on the basis of the evidence which has been obtained. Many of these conclusions can be challenged, for the instrumental equipment was not sufficiently powerful to give really satisfactory data; the despatch of the expedition was a matter of great urgency, and neither the time nor the money was available for more elaborate instruments. In the circumstances it was considered that the best thing to do was to draw attention and give tentative answers to questions which will only be satisfactorily answered as a result of future investigations.

2—Instrumental equipment

The expedition was equipped with the following instruments: one two-component horizontal Wiechert seismograph with stationary mass of 200 kg.; four horizontal Jaggar shock recorders and one Kew-Jaggar vertical shock recorder. In addition sound-ranging apparatus was kindly lent by the War Office for use with hot-wire microphones, the whole to form a shock recorder with an extended time scale for the investigation of shocks of highly local origin.

a—The Wiechert seismograph

This instrument was supplied by Messrs Spindler and Hoyer of Göttingen and is of standard design. The registration is on smoked paper by fine pens, and the time scale is of the order of 1 cm./sec. The stationary mass of the instrument is built up of separate castings which are clamped together, and by gradually increasing the magnitude of the stationary mass the natural period of the instrument can be increased up to a maximum value of about 7 sec.

b—The Jaggar shock recorders

These instruments were designed and constructed at Kew under the direction of Dr Whipple. Drawings of horizontal and vertical instruments are shown in figs. 1, 2

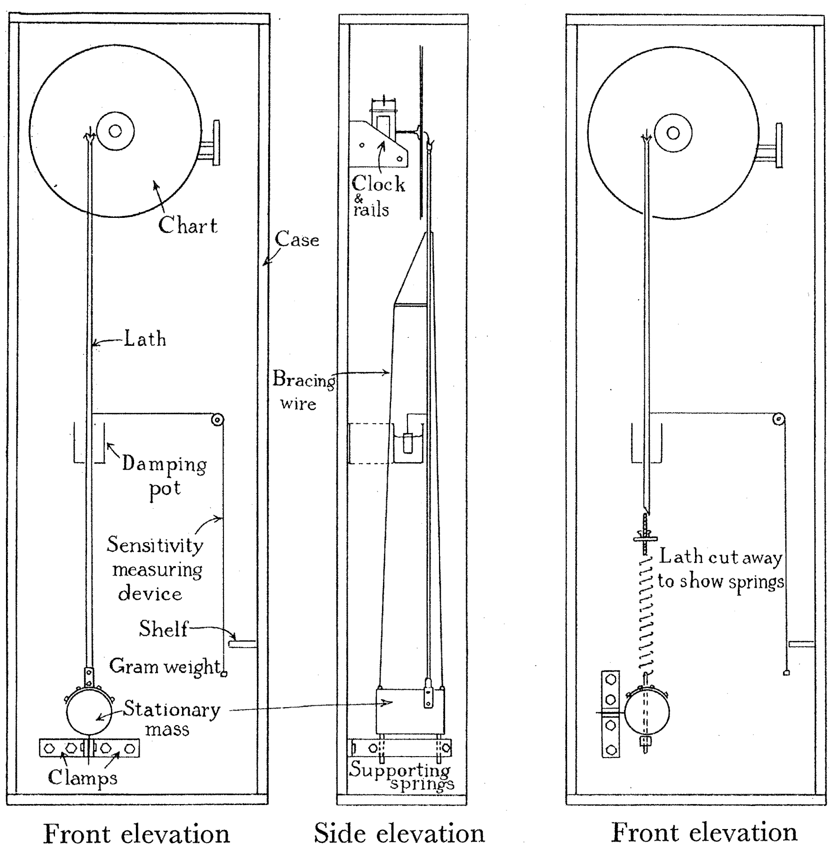

Fig. 1 Fig. 2

Figs. 1 and 2—Horizontal (fig. 1) and vertical (fig. 2) Jagger shock recorder.

and 3. The design is essentially similar to that described by Jaggar (1932), but there are one or two points of novelty, and it will be convenient to give a brief description of the instruments and of their mode of operation. The horizontal instrument consists essentially of an inverted pendulum with a magnifying arm attached. The bob is in the form of a cylindrical mass of lead of 10 lb. weight contained in a thin tube of mild steel, the whole being supported by two flat strips of clock spring. The dimensions of the cross-section of the supporting springs are approximately $8 \times 0{\cdot}5$ mm. The two springs are gripped by the vertical faces of two clamps which are screwed securely to the back of the case of the instrument, the faces being drawn together by two bolts. The effective length of the supporting springs, the distance between the bottom of the bob of the pendulum and the top of the clamps, determines the natural period of oscillation of the pendulum and can be varied. The magnifying arm consists of a light wooden lath, attached at its lower end to an aluminium fitting screwed to the stationary mass, and carrying at its upper end a light steel pen which writes on a

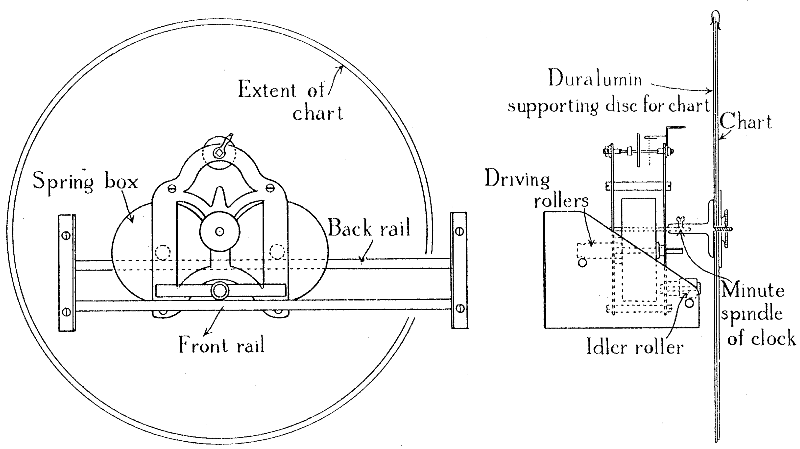

Fig. 3—Clock movement and rails for shock absorbers.

smoked circular disk of Bristol board, 11 in. in diameter. The disk is carried on the minute spindle of a small clock movement so that it makes one complete revolution in 1 hr. The clock is provided with rollers which are mounted on the spindle of the spring drive of the clock, and these rollers move on horizontal rails so that as the springs unwind the whole clock, with the disk attached, is given a horizontal movement along the rails. As a result when the instrument is undisturbed by earthquakes the pen describes a spiral on the smoked chart. In all but one of the instruments installed in Montserrat the size of the rollers mounted on the spring spindle is such that the spacing between the successive lines of the spiral is 3 mm., and one chart lasts for 24 hr. When the instrument is disturbed by the passage of earthquake waves the pen is displaced radially to the spiral and a characteristic record is produced. The length of the magnifying arm, 1 m., is such that the movement of the pen is about fifteen times that of the centre of gravity of the bob of the pendulum, relative to the case of the instrument.

The damping of the instrument is provided by a light aluminium vane attached to the middle point of the vertical lath, which dips into an oil pot. The damping coefficient varies with the extent to which the vane dips into the oil and with the coefficient of viscosity of the oil. It was found desirable to brace the vertical lath with tensed strings to prevent it moving across the allowed direction of motion. Otherwise it was found that during severe shocks the distance between the pen and the paper changed so that the pen did not move truly radially over the paper and a distorted and confused record was obtained. Typical records are shown in fig. 4, Plate 1. The rate of movement of the pen in its spiral path varies as it moves from near the centre outwards, and its mean speed is 5 mm./min.

In an instrument provided by Dr Jaggar, by reducing the moment of inertia of the balance wheel of the clock movement, and by alterations to the gearing, the speed of rotation of the "hour" spindle has been increased five times. The increased time scale which is thus provided can be of considerable value. An example of two records obtained at Olveston with this instrument is included in fig. 4, and it will be seen that the distance between the successive lines of the spiral has been much reduced in comparison with that in the other instruments, from 3·0 to 0·7 mm., by altering the diameter of the driving rollers which provide the lateral movement of the clock. It will be seen that the deflected trace described by the pen during an earthquake has a slight wavering appearance, and this is due in some measure to the fact that the hour spindle of the clock does not move smoothly, but in jerks as a consequence of the escapement mechanism. It should be noticed that the recording is unaffected by the closeness of the lines. In some circumstances it might be of great advantage to have recording of this type, either for obtaining a more extended time scale as in the present instance, or alternatively, using the more usual time scale, to provide an instrument in which the record needs to be changed only once in 4 or 5 days. With such a design it becomes possible to maintain instruments in operation in places which are not easily accessible.

The Kew-Jagger vertical shock recorder, fig. 2, is similar in design to the horizontal instrument. The weight of the bob is taken by a long spring of invar metal, the distance of the bob from the clamps being maintained by thinner springs than in the case of the horizontal instruments.

The method of mounting the shock recorders varied with the nature of the supporting wall at the site chosen. The most satisfactory sites were afforded by "hurricane shelters" in the form of small, low-pitched buildings of reinforced concrete. Here the case of the instrument was fixed to one of the inside walls by means of 3 in. screws driven into wooden blocks or "rawl-plugs" let into the wall. This is the type of mounting employed with the instruments at Olveston, St John's and O'Garra's. At Bethel, Paradise, Waterworks and Gages the instruments were fixed to walls of masonry. The masonry in Montserrat is in general of poor quality owing to the absence of a source of lime in the island. It consists of andesite blocks bound together with an inferior mortar, and it was found desirable to cement two bulks of timber, 3×3 in. in cross-section, into the wall and to screw the instrument to the timber.

The different points in the island at which Jaggar instruments have been or at present are maintained are shown by circles in the map, fig. 11. The line bisecting the circles diametrically shows the bearing of the wall on which the instruments are mounted. The bearing is not accurately known in the case of the instrument at O'Garra's. The vertical shock recorder is maintained at Paradise.

c—The sound-ranging equipment

The sound-ranging equipment consists essentially of a five-string galvanometer with photographic recording. The bromide paper on which the record is obtained passes through the instrument at a speed of about 2 cm./sec., so that the time scale is a hundred times more extended than that in the other shock recorders. For use in conjunction with this instrument the device illustrated in fig. 5 was constructed. The top plate of

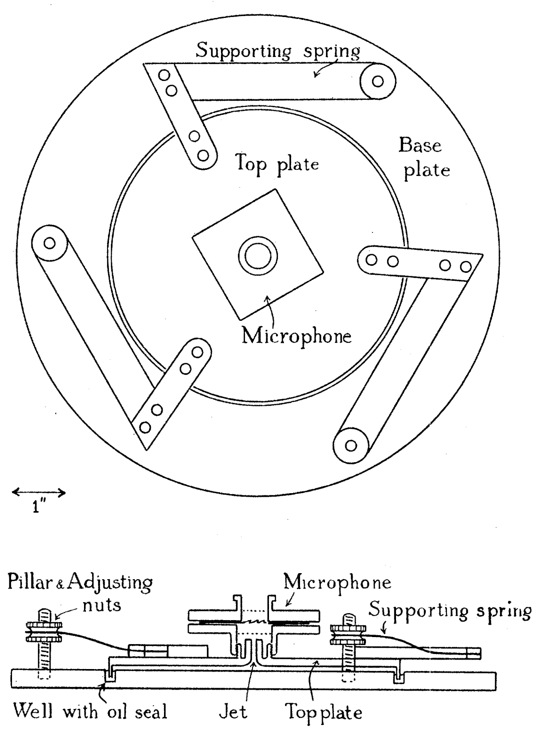

FIG. 5

the instrument, which acts as the stationary mass, is supported by three flat springs attached to it in the manner shown in the diagram. In the position of equilibrium the distance between the flat surfaces of the two plates is about 3 mm., with the rim of the top plate dipping into the circular "well" in the bottom plate. This "well" is filled with oil so that the space between the two plates is sealed except for the central hole in the top plate which is provided with a jet, and over this jet is screwed the grid of the hot-wire microphone. When the instrument is disturbed by the passage of an earthquake, the two plates move relative to one another so that air is forced to flow

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through the jet and past the grid of the microphone. The grid forms one arm of a Wheatstone bridge, and it is maintained hot by the passage through it of an electric current. When the air is forced through the jet, the grid is cooled, its resistance is lowered, the bridge is thrown out of balance, and as a result one of the strings of the galvanometer moves. If the several strings of the galvanometer are connected with similar shock recorders located at different points, the time of arrival of the waves produced by a given earthquake at these points can be determined to within one-hundredth part of a second. The whole method is essentially similar to that employed for the location of oil by the investigation of the earth waves produced artificially by explosions. More satisfactory methods for translating the earth movements into electrical impulses could doubtless be devised, but the method adopted was the most convenient and simple way of adapting the sound-ranging apparatus in the short time available. With four stations equipped in the above manner it was considered that it would be possible to locate the position of the foci of even local earthquakes and to determine their depth by one or more of the conventional methods of seismology.

3—Variation with time of the seismic activity

A general impression of the variation with time of the seismic activity in Montserrat during the past 4 years can be obtained by plotting the daily number of observed tremors from the records made by Mr Gomez, lately Curator of the Grove Botanical

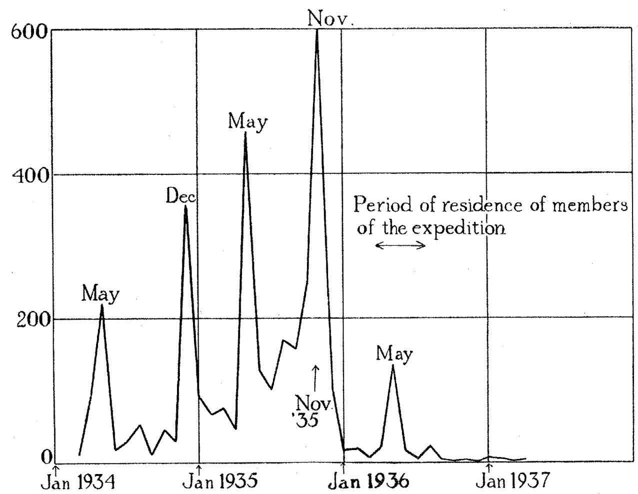

Fig. 6—Number of tremors observed per mensem.

Station, Montserrat, copies of which were kindly placed at the disposal of the members of the expedition. In fig. 6 the monthly numbers of observed tremors are plotted against time. The results have been extended to include the observations made up to the time of writing. It will be seen that the times of most pronounced activity

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occurred at roughly 6-monthly intervals, in May and in November or December. Also that there was a general tendency for the activity to increase until 10–11 November 1935, after which a marked decline set in. Of the more than one thousand earthquakes which occurred in Montserrat between 1933 and 1937 only that which occurred at 18 hr. 27·8 min. G.M.T. on 10 November 1935 was large in the sense of being recorded by seismographs at distant places. This earthquake was recorded at points as widely distant as the Philippine Islands, throughout the U.S.A., and at Kew.

The accounts of residents in the island and the distribution of damage to buildings strongly suggested that most of the earthquakes were highly local in origin, the foci in many cases probably lying under the island. Many of the local residents describe their impressions of some of the more severe of the earthquakes in such terms as "a vertical shock", "vertical bump", etc. Further, the earthquakes were frequently very localized in their effects, being described as severe at one place and trivial at another 5 miles away. It is convenient to state here that the results obtained with the various seismographs show conclusively that the great majority of the shocks do arise from foci under the island.

The most severe earthquakes occurred at times of most pronounced seismic activity as measured by the daily number of tremors. They produced considerable damage to buildings but no loss of life resulted, owing to the fact that most of the population dwell in light wooden structures. The few buildings of reinforced concrete were unaffected, but even the most massive masonry structures, such as the windmill tower on the Gages estate, were severely damaged.

At the time of the departure of the members of the expedition from England the latest news from Montserrat was that of the very active period in November 1935.

4—Distribution and establishment of the Jaggar shock recorders

Preliminary tests with the Jaggar shock recorders were made in a concrete fumigatorium situated at the Grove Botanical Station. The four horizontal instruments were mounted in pairs on two walls at right angles with one another. The instruments were maintained in operation at this place from 26 March until 20 April 1936, and during this period twelve small shocks were recorded and the following tests made. The first problem was to decide the most suitable natural period at which to adjust the instruments. The natural period and the static sensitivity are determined by the effective length of the vertical springs supporting the stationary mass. In order to adjust this length, the bolts drawing the clamps together are loosened and the mass is supported above the top edge of the clamps by a distance piece of appropriate thickness. The clamps are then drawn together again by the bolts and the distance piece removed. A number of pieces of playing cards form a suitable distance piece of variable thickness.

We define the static sensitivity of the instrument in terms of the deflexion of the pen produced by the application of a standard couple to the inverted pendulum system. The standard couple is applied by means of a silk thread attached to the mid-point of the lath and passing out horizontally over a small pulley (see figs. 1, 2). A mass of 1 g. is attached to the free end of the thread, and this can be allowed to hang freely or the tension can be removed from the thread by raising the weight on to a shelf. With the tension applied the pen is deflected, and if the tension is suddenly removed from the thread the pen returns to its equilibrium position in a manner depending on the degree of damping. The position of the damping vane in the oil was always adjusted so that the magnitudes of successive half-swings were in the ratio of five to one. The deflexion produced by the application of the couple can be read directly from the smoked disk.

A direct comparison of the dynamical characteristics of two instruments adjusted to have the same or different static sensitivities was made by comparing the traces produced on the two instruments, as a result of the passage of an earthquake, when they were mounted parallel to one another on the same wall. Observations on four shocks showed that the dynamical sensitivity of the instruments changed very little as the static sensitivity was increased. When the natural periods of the two instruments were equal the two records of the same earthquake showed a detailed similarity, and this similarity was preserved when the static sensitivity, and therefore the natural period, of one of the instruments was changed to a new value. A simple analysis of the dynamics of the instrument shows that this behaviour is to be expected, and that over a considerable range of values the dynamical sensitivity should be nearly independent of the natural period of the instrument for high-frequency earth movements. The most suitable value of the natural period at which to adjust the instruments can therefore be determined by other considerations. When the foci of the earthquakes are local, the "period" of the earth movements produced by them is generally less than half a second, and it is only necessary to make the natural period of the instruments greater than this value. The value of 0·6 sec. was finally chosen rather than a greater value, since it was found that the zeros of the instruments were more stable the lower the period. With this period the static sensitivity was such that the application of a couple of 50 g. wt. cm. produced a deflexion of the pen of 3 mm.

The second problem was to determine the most useful distribution of the Jaggar shock recorders throughout the island. It was found that, with the time scale provided by the ordinary seismographs, the nearness of the foci resulted in there being very little separation, in the record, of the arrival times of the different kinds of earth waves set up by the earthquake. In these circumstances it was not possible to employ any of the usual methods of seismology for determining the positions of the foci and new methods had to be found. It was decided to attempt to locate the foci by an investigation of the amplitude of the horizontal earth movements occurring at different points in the island as a result of the different earthquakes.

For the complete determination of the horizontal movement at any station it is necessary to make observations in two directions at right angles. The preliminary results suggested, however, that in the majority of the earthquakes with which we were dealing, the "amplitudes" of the two components of the earth movement, as recorded on two instruments mounted in the same room on two walls at right angles, were very nearly equal. This result might have been fortuitous and due to the fact that in these instances the shocks were originating at a point or points of which the bearing from the station was roughly equally inclined to the two walls. This question should have been examined by more extended observations, but the month of May was approaching and this month had in the previous 2 years seen a marked increase in the number of tremors. It was therefore considered to be more important to distribute the instruments at various points throughout the island. On the basis of the preliminary results it was decided to distribute the instruments at four different points on the assumption that a single instrument afforded a satisfactory measure of the horizontal intensity of the earth movement at the point at which it was mounted. It was considered that this course would give more information than the alternative plan of obtaining more complete results at two stations only.

The extended observations which have now been made with the Wiechert seismograph, in which both components of the earth movements are recorded, show the conditions in which the observations with a single shock meter give a fairly good estimate of the horizontal earth movements at the station. It may be stated here that the estimates seem to be liable to a large probable error only if two conditions are fulfilled simultaneously:

(*a*) that the bearing of the focus of the earthquake from the station is nearly in line with or nearly perpendicular to the wall on which the instrument is mounted, and

(*b*) that the focus is within one or two kilometers of the station.

Thus the measurements of the records of shocks on the Wiechert seismograph given in Table I show that taking all shocks which have not definitely been ascribed to focal region I, which lies within 2 km. of the seismograph, in more than 80% of the cases the smaller of the two recorded components of a shock has an amplitude at least equal to three-quarters of that of the larger. Of the remaining 20% some will certainly have occurred at foci in the immediate neighbourhood of the station. Assuming a plane polarized disturbance to be emitted from a focus and that the foci were distributed at random, one could expect less than 20 % of the shocks to satisfy the above condition as compared with the 80 % observed.

In the final distribution of the shock recorders, established after 11 May 1936, instruments were maintained at the following points: Gages, Olveston, St John's, Bethel and Paradise. On 22 July an additional instrument was established at O'Garra's. Previously, between 28 April and 11 May, the instruments were differently distributed. In analysing the results the records obtained with the final distribution

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of stations were first considered and certain general principles established. In the light of the experience thus gained it was then possible to return to a consideration of the earlier shocks, Nos. 1–74, Table I, for which the information at our disposal is not so complete.

Table I—Amplitudes of shocks at various stations in mm., except for "Wiechert", which are in cm. "s." denotes that the shock was observed in the record from the corresponding station but was too small to be measured.

	Date	Local time	Gages	Olveston	Water-works	Grove	Wiechert (l.)	Wiechert (r.)	Focal region
*1	Apr. 28	20.21	3·1	0·8	0·6	3·0	2·4	0·8	I
*2	,, 29	21.49	6·1	4·1	2·9	2·4	2·3	1·3	I
*3	,, 29	21.49	0·8	0·3	0·25	0·2	0·5	0·6	I
*4	,, 29	22.24	3·5	1·5	1·35	2·3	1·9	1·1	I
5	May 1	08.02	1·55	—	—	1·0	0·75	0·3	I
6	,, 1	23.25	1·5	0·3	—	—	0·37	—	—
*7	,, 2	04.28	22·8	6·0	12·0	6·0	9·8	—	II
*8	,, 2	04.31	9·8	5·0	6·0	4·0	6·6	—	II
9	,, 2	06.24	1·0	—	—	—	0·37	—	—
*10	,, 2	07.03	5·7	2·3	3·8	1·5	3·0	—	II
11	,, 2	08.46	4·0	0·7	1·6	—	—	—	II
12	,, 2	08.46	1·6	0·35	0·7	—	—	—	—
13	,, 2	14.39	2·9	0·2	0·7	—	0·67	0·55	II
*14	,, 2	16.00	1·0	0·3	—	—	0·4	0·25	—
*15	,, 2	16.03	2·0	0·7	0·7	0·7	1·65	0·5	—
16	,, 2	17.38	21·8	10·4	18·5	6·3	—	—	I
17	,, 2	19.54	0·85	—	0·2	—	—	—	—
18	,, 2	23.01	1·0	—	0·3	—	—	—	—
*19	,, 3	02.45	5·0	1·1	1·6	1·2	1·1	0·7	II
*20	,, 3	02.47	2·6	0·8	1·3	0·7	0·75	0·6	II
21	,, 3	02.53	0·65	—	—	—	0·18	0·10	—
22	,, 3	03.03	0·45	—	—	—	0·05	0·05	—
23	,, 3	03.22	0·95	—	—	—	0·08	0·07	—
24	,, 3	03.48	1·9	0·2	0·3	0·35	0·28	0·25	—
25	,, 3	05.49	1·0	—	—	—	0·18	0·17	—
26	,, 3	07.33	1·3	—	0·2	—	0·16	0·12	—
*27	,, 3	11.51	7·6	1·4	1·9	—	1·75	1·4	II
*28	,, 4	06.40	4·5	1·1	1·8	1·2	1·38	1·0	II
29	,, 4	06.50	0·5	—	—	—	0·12	0·12	—
30	,, 4	06.53	1·0	—	0·5	0·2	0·28	0·28	II
31	,, 4	11.20	0·3	—	0·3	—	0·22	0·14	—
32	,, 4	12.09	0·6	—	—	—	0·27	0·26	—
33	,, 4	12.31	0·3	—	0·15	—	0·12	0·11	—
*34	,, 4	15.23	2·2	0·5	1·1	—	0·78	0·75	II

	Date	Time	Gages	Olveston	Water-works	St John's	Wiechert (l.)	Wiechert (r.)	Focal region
35	May 5	14.34	1·0	—	—	—	0·17	0·19	II
36	,, 5	17.00	0·5	—	—	—	0·12	0·12	II
37	,, 5	23.20	5·0	3·2	4·6	3·0	2·1	2·0	II
38	,, 6	06.22	0·7	—	—	—	0·11	0·07	—
*39	,, 6	15.00	1·6	0·3	0·5	0·15	0·85	0·55	—
*40	,, 6	19.16	0·5	—	—	0·25	0·45	0·35	II
*41	,, 6	21.58	0·6	0·15	0·4	—	0·40	0·36	—
*42	,, 6	22.09	0·4	—	0·3	—	0·24	0·32	II
43	,, 7	08.46	0·7	—	—	—	0·09	0·07	—

TABLE I—(*continued*)

	Date		Time	Gages	Olveston	Water-works	St John's	Wiechert (l.)	Wiechert (r.)	Focal region
*44	May	7	09.32	0·65	0·15	0·25	—	0·45	0·33	—
*45	,,	7	15.30	0·9	—	0·6	0·25	0·40	0·28	—
46	,,	7	15.43	0·9	—	0·2	—	0·32	0·29	—
*47	,,	7	19.02	0·6	0·25	0·35	—	0·44	0·40	—
48	,,	7	19.51	32·0	14·0	17·2	21·8	Pens thrown		V
49	,,	7	19.58	1·0	0·55	0·65	0·7	,,		V
50	,,	7	20.04	0·3	0·25	0·3	0·3	,,		—
51	,,	7	20.15	0·9	0·20	0·5	—	,,		—
*52	,,	7	21.32	0·9	0·7	1·1	0·4	0·50	0·52	—
*53	,,	7	21.57	0·6	0·4	0·5	0·45	0·28	0·25	—
*54	,,	8	04.30	1·2	0·5	0·8	0·5	0·50	0·50	—
*55	,,	8	05.06	1·4	1·1	1·5	1·25	0·45	0·45	—
56	,,	8	13.08	0·7	—	0·2	0·1	0·38	0·36	—
57	,,	8	22.06	0·9	0·45	0·4	0·25	0·28	0·21	—
58	,,	9	08.25	0·45	—	—	—	0·22	0·17	—
*59	,,	9	18.11	1·50	—	—	—	0·65	0·45	—
60	,,	9	23.56	62·7	49 (?)	—	17·2	Pens thrown		I
61	,,	9	23.59	1·5	—	—	—	—	—	I
62	,,	10	00.02	14·5	4·0	—	3·8	—	—	I
63	,,	10	00.13	3·8	3·6	—	0·8	—	—	I
64	,,	10	00.17	11·4	7·2	—	1·2	—	—	I
65	,,	10	00.23	2·9	2·2	—	0·2	—	—	I
66	,,	10	02.07	3·4	1·6	—	0·15	—	—	I
67	,,	10	02.15	0·8	1·2	—	—	—	—	I
68	,,	10	02.20	0·2	—	—	—	—	—	—
69	,,	10	02.47	1·9	—	—	—	—	—	—
70	,,	10	02.50	2·0	—	—	—	—	—	—
71	,,	10	11.07	0·6	—	—	—	—	—	—
72	,,	10	21.34	0·85	—	—	—	0·20	0·22	—
73	,,	10	22.25	0·65	—	—	—	0·22	0·25	—
74	,,	11	03.04	0·95	—	—	—	0·37	0·31	—

	Date		Time	Gages	Olveston	St John's	Bethel	Wiechert (l.)	Wiechert (r.)	Focal region
75	May	11	13.07	0·25	—	—	—	0·12	0·10	—
*76	,,	11	16.45	1·3	0·65	s.	0·45	1·55	0·95	I
77	,,	11	19.25	0·65	—	—	—	—	—	V
*78	,,	11	20.34	2·0	0·75	1·5	3·1	1·15	0·75	V
79	,,	12	01.33	1·2	0·4	0·4	0·4	0·95	0·42	I
80	,,	12	12.14	2·05	1·4	s.	s.	1·13	0·95	I
*81	,,	12	17.36	1·8	0·9	0·5	2·1	0·90	0·70	II
*82	,,	13	00.56	1·2	1·2	0·5	1·0	1·60	1·25	I
83	,,	13	01.15	4·8	3·9	0·4	1·2	Pens thrown		I
84	,,	13	01.16	1·1	1·0	0·1	0·25	—	—	I
85	,,	13	06.54	1·7	1·4	0·65	1·6	—	—	—
86	,,	13	07.49	1·95	0·85	0·7	2·1	—	—	II
87	,,	13	08.02	—	—	—	0·25	—	—	II
88	,,	13	09.20	3·4	0·75	0·5	1·2	—	—	II
89	,,	13	13.13	0·5	—	—	0·35	0·23	0·12	—
90	,,	13	17.57	0·3	—	—	—	0·12	0·13	—
*91	,,	13	19.12	2·2	1·5	0·8	2·8	1·00	1·00	—
92	,,	13	23.35	0·5	—	—	—	1·10	0·48	I
93	,,	14	06.05	0·65	—	—	0·65	0·24	0·24	IV
94	,,	15	08.13	1·1	0·85	0·25	0·95	0·34	0·31	—
95	,,	16	06.04	0·5	—	0·15	—	0·14	0·11	—
96	,,	17	03.42	16·5	3·9	3·5	8·5	5·20	Pen thrown	—

Table I—(*continued*)

	Date	Time	Gages	Olveston	St John's	Bethel	Wiechert (l.)	Wiechert (r.)	Paradise	O'Garra's	Focal region
97	May 17	03.48	1·5	0·5	0·55	1·3	0·55	0·60	—	—	—
98	,, 17	03.52	0·4	—	—	0·3	0·22	0·25	—	—	—
99	,, 17	04.30	0·55	—	—	—	0·27	—	—	—	—
*100	,, 17	09.35	1·25	—	0·15	1·3	0·40	0·30	—	—	—
101	,, 17	17.23	0·75	—	—	—	0·08	0·06	—	—	—
*102	,, 17	23.27	1·9	0·75	0·65	1·7	0·87	0·57	—	—	—
103	,, 20	19.54	0·65	—	—	0·3	0·55	0·27	—	—	I
*104	,, 21	15.06	1·9	1·25	0·1	0·2	1·18	1·00	—	—	I
105	,, 21	16.52	0·4	0·4	—	—	0·13	0·12	—	—	—
106	,, 22	06.47	—	—	—	0·35	0·07	0·06	—	—	—
107	,, 22	10.37	0·8	0·6	s.	0·3	1·9	2·1	1·4	—	I
108	,, 25	18.10	0·75	0·7	s.	0·2	0·83	0·57	1·0	—	I
109	,, 26	01.58	—	—	—	—	0·34	0·22	0·65	—	—
110	,, 27	19.43	0·4	—	—	—	0·08	0·09	0·4	—	—
111	,, 28	02.04	0·6	0·6	1·2	0·7	0·53	0·45	0·25	—	—
112	,, 28	12.00	1·1	0·3	0·3	1·3	—	—	1·35	—	—
113	,, 29	02.20	0·65	—	—	—	—	—	—	—	—
114	,, 30	01.56	—	—	—	—	—	—	0·3	—	—
115	,, 30	02.59	—	—	—	—	—	—	0·45	—	—
116	,, 31	22.41	8·8	4·15	3·2	4·2	9·8	Pen thrown	5·0	—	—
117	June 1	12.31	1·3	—	—	—	1·06	0·75	—	—	—
118	,, 3	22.18	1·15	0·5	0·6	1·0	0·48	0·34	0·4	—	—
119	,, 4	04.30	0·35	0·35	0·8	1·1	0·28	0·28	—	—	—
120	,, 5	05.42	1·25	0·85	0·75	1·0	0·61	0·53	—	—	—
121	,, 6	07.26	5·1 (?)	1·85	0·4	0·35	Pens thrown		0·8	—	I
*122	,, 6	09.42	0·75	0·5	0·55	0·5	0·55	0·47	—	—	—
*123	,, 7	17.23	0·85	0·75	0·35	1·1	0·56	0·40	—	—	—
*124	,, 8	10.34	4·45	1·05	1·05	2·3	0·98	0·82	2·4	—	—
125	,, 8	10.36	0·9	—	—	0·45	0·15	0·19	0·4	—	—
126	,, 8	13.21	1·2	—	—	0·45	0·20	0·21	1·1	—	—
*127	,, 9	13.22	2·35	4·05	1·25	1·25	1·55	1·27	1·65	—	—
*128	,, 17	17.40	0·7	1·15	s.	s.	0·57	0·57	s.	—	—
*129	,, 17	22.37	0·3	1·0	s.	s.	0·42	0·26	s.	—	—
130	,, 19	23.12	1·0	1·5	1·9	2·6	3·40	2·70	0·25	—	—
131	,, 22	21.44	0·75	0·35	0·7	1·3	0·28	0·26	0·75	—	—
132	,, 22	22.45	0·65	0·30	0·65	1·1	0·25	0·25	0·45	—	—
133	,, 26	07.44	1·1	—	—	—	0·19	0·19	0·9	—	—
134	,, 30	08.45	5·2	0·90	0·50	5·2	4·95	2·65	3·6	—	—
*135	,, 30	23.30	0·85	0·90	2·0	2·3	0·53	0·49	1·3	—	III
*136	July 1	05.46	2·6	2·0	6·6	6·9	2·28	1·82	3·1	—	III
*137	,, 1	05.49	2·1	1·5	4·1	4·75	1·25	1·10	3·4	—	III
138	,, 4	—	—	—	—	—	0·50	0·28	—	—	—
139	,, 14	—	7·8	—	—	—	0·84	1·05	—	—	—
*140	,, 31	09.14	1·13	0·83	1·62	1·85	0·55	0·60	0·73	0·37	III
141	Aug. 3	01.50	No record	0·80	—	—	0·18	0·16	—	—	—
142	,, 3	07.50	1·02	1·47	0·33	0·88	0·40	0·46	1·05	—	I
143	,, 9	10.08	0·40	0·21	s.	s.	0·13	0·14	0·10	—	—
144	,, 9	11.15	0·60	0·31	—	s.	0·18	0·22	0·20	—	—
145	,, 11	08.57	1·52	0·72	—	—	0·56	0·53	0·75	—	—
146	,, 12	10.13	0·88	0·72	—	—	2·3	2·1	—	0·29	I
147	,, 20	06.24	0·75	0·80	No record	No record	0·50	0·46	—	—	I
148	,, 20	08.42	0·30	0·40	,,	—	No record		—	—	—
149	,, 24	04.22	0·30	0·70	—	—	0·25	0·28	—	—	I
150	,, 24	11.20	0·25	—	—	—	0·25	0·30	—	—	—
151	,, 27	08.05	22·0	10·5	3·8	10·8	Pens thrown		No record	2·1	—
152	,, 27	08.06	0·8	0·4	s.	s.	,,		,,	s.	—
153	,, 27	08.08	5·6	3·2	1·7	1·9	No record		2·2	0·4	I

TABLE I—(*continued*)

	Date	Time	Gages	Olveston	St John's	Bethel	Wiechert (l.)	Wiechert (r.)	Paradise	O'Garra's	Focal region
154	Aug. 27	08.21	1·2	1·5	s.	0·4	No record		0·3	—	I
155	,, 27	08.40	1·2	0·8	s.	0·4	,,		0·8	—	I
*156	,, 27	09.01	1·3	0·7	s.	0·4	0·8	0·5	0·55	—	I
*157	,, 27	09.13	0·35	0·3	—	—	0·63	0·29	—	—	I
158	,, 27	09.16	6·2	3·8	1·0	2·8	Pens thrown		2·2	0·3	I
159	,, 27	09.17	0·7	0·4	s.	s.	No record		—	—	I
*160	,, 27	09.28	2·15	1·1	0·6	0·3	2·2	1·1	0·7	—	I
161	,, 27	09.40	0·35	0·2	—	—	0·38	0·30	—	—	I
162	Sept. 1	13.52	0·40	—	—	—	1·05	0·75	—	—	I
163	,, 3	20.28	0·7	1·2	0·30	0·85	0·25	0·23	—	—	—
164	,, 15	21.30	0·75	—	—	—	No record		—	—	—
165	,, 21	11.43	0·80	—	—	—	0·27	0·29	—	—	I
166	,, 30	08.19	1·1	1·2	0·2	1·1	No record		1·3	—	—
167	,, 30	17.00	1·3	1·2	—	1·2	0·95	0·65	—	—	—
168	Oct. 2	20.34	0·45	No record	—	—	0·95	0·49	—	—	—
169	,, 25	17.11	9·1	4·7	No record	9·0	9·0	9·5	3·5	2·2	—
170	,, 31	16.20	0·45	—	—	—	0·18	0·20	—	—	—
171	Nov. 2	19.36	0·25	—	—	—	No record		—	—	—
172	,, 10	14.02	0·50	—	—	—	0·16	0·14	—	—	—
173	,, 20	23.55	0·3	0·5	—	—	—	—	—	0·1	—
174	,, 22	10.16	7·4	5·3	1·0	2·8	Pens thrown		1·3	—	—
175	,, 27	20.01	1·2	No record	3·1	1·3	3·0 (?)	3·0 (?)	1·1	—	—
176	,, 28	07.51	0·2	,,	—	—	—	0·4 (?)	—	—	—
177	Dec. 4	14.30	6·3	4·0	1·5	1·7	Pens thrown		1·6	3·1	—
178	,, 20	22.35	0·9	—	—	—	0·56	0·43	—	—	—
179	,, 29	08.49	5·6	3·0 (?)	3·8	8·1	—	3·1	3·2	2·9	—
180	,, 30	02.03	3·4	No record	2·5	2·1	1·65	1·35	0·6	0·2	—
181	Jan. 4	06.40	1·6	2·0	1·6	0·9	1·05	0·70	0·4	—	—
182	,, 11	15.35	0·9	0·6	—	—	0·30	0·38	—	—	—
183	,, 20	03.21	5·3	6·8	3·4	4·1	Pens thrown		2·1	2·0	—
184	,, 20	03.23	4·0	4·8	2·6	3·4	,,		1·7	1·3	—
185	Feb. 23	04.30	4·9	3·8	0·7	2·6	Wiechert		1·3	1·2	—
186	,, 23	05.43	0·9	0·8	—	—	touching		—	—	—
187	,, 24	00.17	2·7	1·2	—	1·0	stops		—	—	—
188	Mar. 26	09.24	—	—	No record	3·9	0·95	0·86	1·7	—	—
189	,, 27	13.30	0·9	2·2	—	—	0·75 (?)	1·02	0·2	—	—
190	,, 31	19.30	3·0	1·7 (?)	1·9	3·4	—	1·40	—	—	—
191	Apr. 1	16.45	2·6	0·7	1·0	2·9	0·92	1·15	1·9	—	—
192	,, 5	04.05	11·2	26·3	9·3	8·6	Pens thrown		2·5	2·1	—
193	,, 6	12.07	0·6	0·9	No record	—	—	0·69	—	—	—
194	,, 8	02.17	0·3	—	,,	—	—	0·58	—	—	—
195	,, 21	23.24	0·75	1·2	0·3	No record	—	0·65	—	—	—
196	,, 29	10.49	0·60	0·2	0·9	0·75	0·55	0·60	0·3	—	—
197	May 5	18.16	7·7	13·1	3·8	3·6	Pens thrown		2·2	—	—
198	,, 10	16.28	0·35	—	—	—	0·28	0·32	—	—	—
199	,, 19	12.39	1·40	2·0 (?)	1·9	1·3	1·25	1·20	0·6	—	—
200	,, 26	06.49	0·60	1·1	—	No record	0·25	0·47	—	—	—

5—MOUNTING OF THE WIECHERT SEISMOGRAPH

The Wiechert seismograph has been maintained continuously in operation since 28 April 1936, except for a break of 5 days, at the Grove Botanical Station. In the first instance it was erected on a thin concrete floor in an outhouse attached to the Agricultural Station. In this instrument the stationary mass is supported on a pair of Cardan springs, and for the first months only about one-third of the full mass was employed. This precaution was taken because the accounts of local residents strongly suggested that very large vertical accelerations had occurred during previous earthquakes. On 12 December 1934 at Gages, for example, an iron bedstead, constructed in a familiar fashion with knuckle joints at the four points where the main frame of the bed is secured to the four legs, was taken to pieces at two of the joints. On other occasions at this place the telephone receiver was lifted off its hook and six tea-cups on a tray, full of tea, were emptied of their contents without a single cup being overturned. These effects strongly suggest impulsive vertical accelerations greater than that of gravity, and it was considered that if similar accelerations occurred with the full mass of the seismograph in position the Cardan spring system would be likely to buckle. This danger was excluded, except in the case of extremely great accelerations, by employing a smaller mass so that the natural period of the instrument was only 2 sec. For the investigation of local shocks this comparatively low period is not a disadvantage.

It was stated in § 3 that the accounts of individual residents in the island strongly suggested that the shocks were local in origin, many of the foci probably lying under the island. Miss E. M. Gillie, for example, of the Cocoanut Hill Hotel, Montserrat, had experienced all the earthquakes of the present series in Montserrat, and in addition she had felt the passage of a number of shocks during a long previous residence in Antigua. She stated that there was a characteristic difference between her impressions of the present earthquakes and those felt in Antigua. She found the recent shocks in Montserrat peculiar in that they occurred with great suddenness with very little preliminary warning, whereas those with which she was familiar in Antigua always gave warning of their approach by a preliminary tremor lasting sometimes for 20 sec.

The origin of this impression is clearly to be seen in the records obtained with the Wiechert seismograph. Characteristic traces obtained with this instrument are shown in figs. 7, 8 and 9 (Plate 2–4), and it will be seen that the greatest earth movement occurs within 1 or 2 sec. of the beginning of the shock. It will be convenient to refer to the small spur which precedes the main movement as the P wave, and to the main movement as the S wave. Whatever the nature of the waves, the absence of resolution of the two wave motions, with the time scale provided by the instrument, clearly indicates that the foci are highly local, and this conclusion is confirmed by the contrast provided by the records of the few more distant shocks which are discussed in § 11. The preliminary tremor, described by Miss Gillie as characteristic of the shocks which she observed in Antigua, corresponds presumably to the arrival of the P wave. Similar descriptions of their impressions of earthquakes during the present series, in which they refer to preliminary tremors, have been given by observers in Antigua.

It is stated above that there is no resolution of the P and S waves with the time scale provided by the instrument. The information given by the records obtained with the high-speed Jaggar shock recorder shows that such resolution is possible if the time scale is sufficiently extended. Thus the records (*f*) and (*g*) of fig. 4 show the *P* and *S* components clearly resolved, although the focus of the shocks was only 1 or 2 km. from the station.

After the earthquakes in May 1936 the period of the instrument was gradually increased up to a final value of 7 sec. in order to be able to detect really distant earthquakes. With this longer period the instrument is much more sensitive to changes in tilt and the limitations of the original site became more obvious, large deflexions of the pen taking place when the observer walked round the instrument (see the record for shock No. 136, fig. 9). Further, the instrument was only protected by a wooden building of light construction which would have been destroyed during a hurricane. It was therefore necessary to make more adequate provision for the permanent installation of the instrument, and on 18 July 1936 it was transferred to a specially constructed building of reinforced concrete. The instrument was erected in this house on a concrete block 40 in. square in plan and 30 in. deep, with extensions at the four corners protruding into the earth like the fangs of a molar tooth. Provision was also made in this house for the smoking and fixing of the records from the Jaggar shock recorders so that the building could be made to serve as a centre for all the seismic observations.

6—Erection of the sound-ranging equipment

This instrument and the motor generator and batteries for operating it were erected at the Cocoanut Hill Hotel, and the leads for three microphones were installed, one at the Hotel, one at Gages, and one at the Grove Botanical Station. The leads to the microphones were made with wires on the ordinary overhead telephone system. Following the great decrease in the daily number of observed tremors which followed the severe earthquake of 10 November 1935 there was only one period during which it would have been possible to run the sound-ranging equipment. This was in the first two weeks of May, and it had not been possible to erect the instrument in time for this period of increased activity. The photographic paper on which the record is made costs about 15*s*. per hour of operation, and unless shocks are occurring at a rate of more than ten or twenty a day the running costs are prohibitive.

7—Observers in other islands

Through the kindness of H.E. the Governor of the Leeward Islands, Sir Gordon Lethem, it was possible to arrange for regular accounts of any earthquakes felt in other of the Leeward Islands to be placed at the disposal of the members of the expedition. We are much indebted to the gentlemen who are acting as observers in the islands of St Christopher*, Nevis, Antigua, and Dominica, for their assistance. In

* Known also as St Kitts.

certain instances the additional information which was thus obtained has proved of considerable value.

8—Results obtained with the Jaggar shock recorders

In analysing the results obtained with the Jaggar shock recorders it is convenient to define a quantity, the amplitude of the horizontal earth movement at any station, resulting from the passage of an earthquake, as the maximum excursion of the pen in the recorded deflexions. This definition thus ignores all details of the recorded movement. In Table I the results of the measurements on all the shocks recorded on the Jaggar shock recorders between 28 April 1936 and 8 July 1937 are given. The numbers give the amplitude of the shocks at the different stations in millimetres. Included in the table are the results on the measurements of the Wiechert seismograph records, one column for each component of the instrument. These last numbers give the amplitude of the shocks as recorded on this instrument in centimetres, but the results can be directly compared with the other figures, since the amplification of the Wiechert instrument is approximately ten times that of the Jaggar shock recorders.

In order to facilitate a comparison of the results for the different shocks it is convenient to represent them pictorially. This is done in the following manner. The amplitude at any station is first expressed as a fraction of the amplitude of the shock as recorded at Gages. The values at the different stations are then plotted as a succession of points lying on a series of parallel straight lines, one line for each station, the distance of each point above a common base-line being proportional to the relative amplitude at the corresponding station. The points are then joined by straight lines and a pattern results. The only object of this procedure is to give a quick and convenient method of comparing the amplitude distribution for the different shocks, since visual patterns can be much more easily compared and remembered than a succession of figures. Included in figs. 7, 8 and 9,* which show the Wiechert records of a number of shocks, are the corresponding amplitude distributions among the Jaggar stations.

An inspection of the figures of all the shocks shows at once that there are striking similarities between many of them, similarities which are repeated much too frequently to be fortuitous. If the curves are replotted with the stations taken in a different, random order, unfamiliar patterns are obtained. The question then arises as to whether the patterns are due to some instrumental peculiarity. An examination of the results shows, however, that frequently shocks occur in quick succession which give distributions of amplitude which are quite different one from another, although each may be closely similar to distributions which have occurred some time previously or which occur subsequently (cf. shocks Nos. 134 and 135, Table I). We therefore conclude that the results are not vitiated by any instrumental deficiency.

* The records of both components are reproduced in these figures, the "left" component above the "right". The corresponding directions of movement are shown in fig. 11.

The most natural explanation of the similarities which exist between many of the patterns is that they are produced by earthquakes originating at the same or closely neighbouring foci, so that a given amplitude distribution corresponds to one particular focus or relatively restricted focal region. In such cases such a similarity is to be expected independent of any directional properties of the instruments, since the bearing of the focus and the distance from each of the stations remain constant.

This conclusion is strongly reinforced by a detailed examination of the records obtained with the Wiechert seismograph. In fig. 9 the records of four shocks are reproduced together with the corresponding amplitude patterns. It will be seen that the patterns are similar and, accepting the argument of the previous paragraph, we should conclude that the shocks originated at the same focus. A careful comparison of the seismograph records shows in addition that there is a detailed similarity between the traces produced by the four shocks. A similar set of records and the corresponding patterns are shown in figs. 7 and 8. This detailed similarity appears only when the amplitude distribution for the shocks are also closely similar. We therefore conclude that there are a number of active foci at which earthquakes recur comparatively frequently. Each distinctive focus is designated by a Roman numeral, and this numeral is given in the last column of Table I against the corresponding shocks.

9—Location of the foci of the shocks

In order to estimate the position of the foci from the amplitude distributions produced by the different shocks it is necessary to make certain simplifying assumptions. The actual amplitude of the earth movements produced at a station as a result of the passage of a given earthquake will depend in actual fact on a number of factors of which it is difficult to estimate the influence. Such factors are the details of the local and distant topography, the nature of the building on which the instrument is mounted, the bearing of the wall on which the instrument is mounted relative to the direction of the focus from the station, and other factors. As a first approximation we assume that the amplitude recorded by the Jaggar shock recorders varies inversely as the distance of the focus from the station and is independent of the other factors.

In the case of distant earthquakes the variation of amplitude with $1/r$ can be regarded as a roughly verified empirical rule. The question has been discussed theoretically by a number of authors (Lamb 1904; Jeffreys 1927, 1935), and it has been shown that such a relation should hold only for a bodily wave undisturbed by discontinuities. This relationship should be seriously affected by reflected waves. For a plane free surface the displacement in P or SV should vary as $1/r^2$. The fact that the observed motion is better represented by $1/r$ than by any other simple power relationship suggests that there are other factors influencing the amplitude which have not been allowed for in the theory.

In the case of surface waves the assumed variation also appears to be reasonable. The total energy crossing a line element at a distance r from the focus should be inversely proportional to $1/r$. Since the time of passage of the waves past the element will be roughly proportional to r, the time mean of the energy in the disturbance will vary roughly as $1/r^2$ and the amplitude as $1/r$, provided there is no dissipation of energy as the waves proceed.

Assuming that the amplitude as recorded by a Jaggar shock recorder is inversely proportional to the distance of the station from the focus, the position of the focus of any shock for which the amplitude distribution is known can be roughly estimated.

In several instances it is necessary to appeal to other considerations in estimating the position of the focus. Thus shock No. 134 gave rise to the following amplitudes relative to Gages: Olveston 0·17, St John's 0·10, Bethel 1·0. It is not possible to find a point which gives an amplitude distribution in accordance with the observations on the assumption that the amplitude varies only with the distance from the focus. We suggest that in this case the focus was relatively high up in the Soufrière Hills, roughly equidistant between Gages and Bethel, and that the small amplitude at Olveston and St John's may be due either to the fact that owing to the details of the local topography the direct waves from the focus could not reach these stations or to the extremely broken nature of the intervening country.

Further information on the effect of the intervening topography on the amplitude of the shocks as recorded at a given station is provided by the results obtained with the distant shock of 19 June, No. D 8, the Wiechert record for which is shown in fig. 14. It is estimated that this shock originated at a distance of about 45 km. from the instrument, and we should therefore expect that there would not be large variations in the amplitude as recorded at the various Jaggar stations on the assumption that the amplitude varies only inversely as the distance of focus from the station. The relative amplitudes actually observed are shown in fig. 10, and it will be seen that the variation is large.* The focus of the earthquake was to the north of the island, and these results suggest that in the case of the waves from such relatively distant earthquakes a station may be shielded to some extent by mountain masses in the path of approaching waves. Such a shielding action might be expected if the waves responsible for the largest movements composing the shock were surface waves.

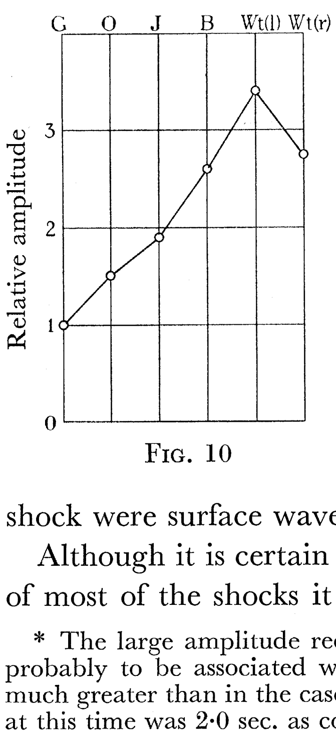

Fig. 10

Although it is certain that effects of this kind must influence the results, in the case of most of the shocks it is possible to estimate the position of the epicentre without

* The large amplitude recorded by the Wiechert seismograph in the case of this distant shock is probably to be associated with the fact that the mean period of the recorded earth movements is much greater than in the case of the more local shocks, and that the natural period of the seismograph at this time was 2·0 sec. as compared with 0·6 sec. for the Jaggar shock recorders.

appealing to such considerations in interpreting the amplitude patterns. The results derived from the method were briefly described in the preliminary report. It was there pointed out that the final allocation of suggested foci was more likely to be free from serious error as a result of the fact that certain relationships should exist between the patterns corresponding to different suggested foci. The whole complex of suggested foci must in fact satisfy the condition that there is no sudden change in the amplitude distribution in going from one shock to a neighbouring one, except when the focus is in the immediate neighbourhood of one of the stations, in which case the amplitude at this station may change considerably relative to that recorded at the other stations (compare fig. 7). The final conclusions are therefore checked to some extent by one shock against another.

These results can be examined in the light of the information given by the Wiechert records. If, for example, the details of the shocks originating at focal region I (see fig. 7) which is close to the Grove Botanical Station where the Wiechert seismograph is located, are compared with those from focal region III (see fig. 9) on the other side of the island, it will be seen that there is a characteristic difference in the form of the records. Whereas a very near shock is characterized by a sharp initial impulse which quickly dies away so that the earth movements have entirely disappeared within half a minute, a more distant shock shows a small preliminary spur associated with the arrival of the P wave and the earth movement has not entirely disappeared at the end of 3 min. Further, the large movement corresponding to the arrival of the S wave in the case of the "far" shock is followed by other movements of almost equal magnitude some seconds later.

This characteristic difference is easily explained in terms of the suggested location of the two foci. The actual earth movements at any station are due both to the waves transmitted directly through the elastic solid crust to the station from the focus, and to waves which have suffered reflexions and refractions in the complicated crustal formation which forms the island edifice. As a first approximation let us assume that the relative intensities of the direct, reflected and refracted waves vary inversely as the length of path of the respective waves from the focus to the station. In the case of the near focus let us suppose that the direct wave takes 1 sec. to reach the instruments, the focus being, say, 2 km. away and the speed of propagation 2 km./sec. Waves which arrive half a minute later will have travelled approximately 60 km. in passing from the focus to the station, and their amplitude will therefore be only about one-thirtieth of that of the direct wave. In contrast with this result, in the case of a focus distant 10 km. from the station, the direct wave arrives 5 sec. after the occurrence of the earthquake. A wave which arrives another 30 sec. later will have travelled a distance of 70 km. and will therefore be of one-seventh the amplitude of the original wave. These considerations therefore explain why the movements associated with a very local shock die away much more rapidly than those of a more distant one. Further, the suggested locations of the different foci are in agreement with the

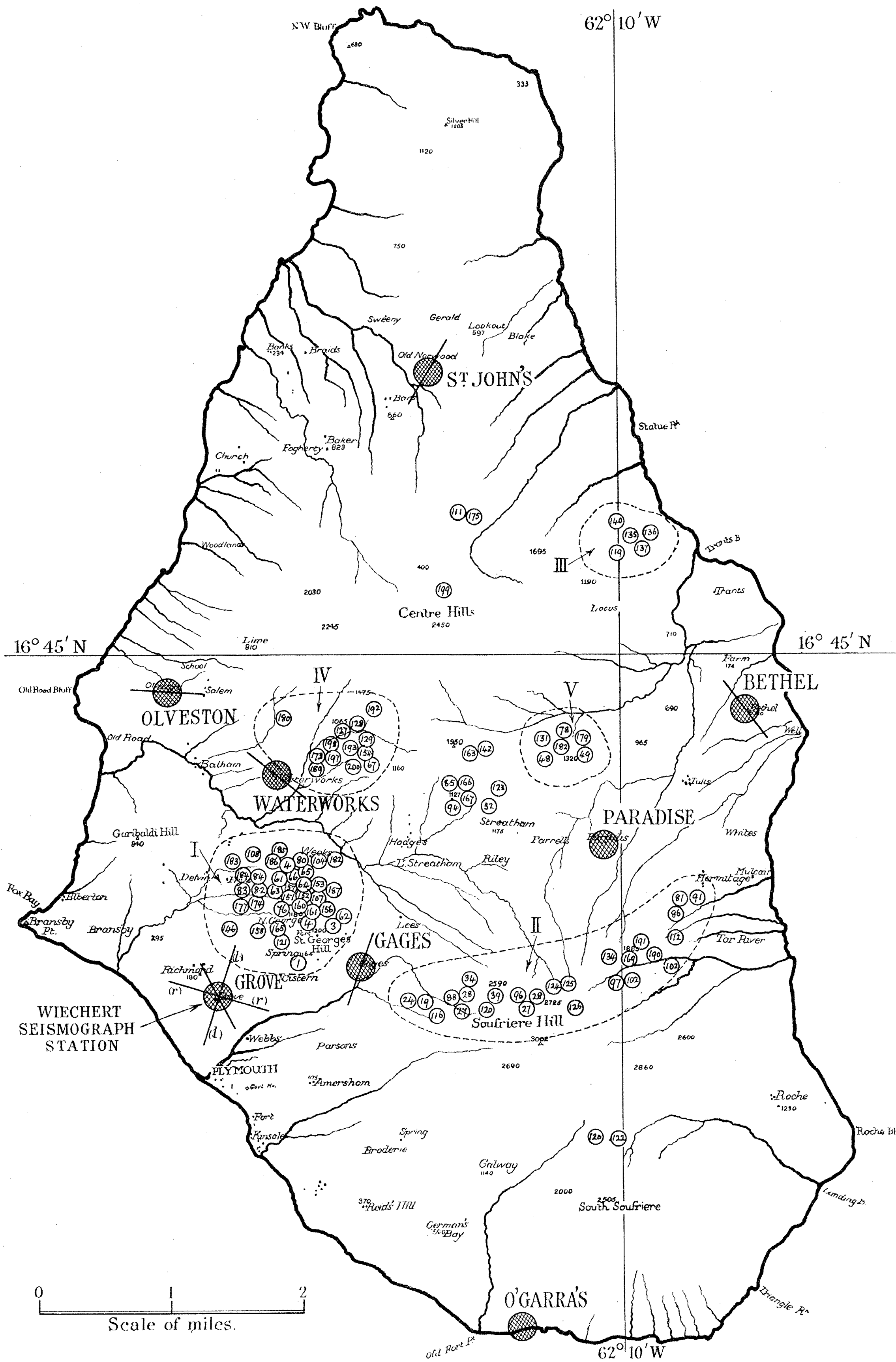
62° 10′ W
16° 45′ N
16° 45′ N
62° 10′ W
ST. JOHN'S
OLVESTON
WATERWORKS
PARADISE
BETHEL
GAGES
GROVE
O'GARRA'S
WIECHERT
SEISMOGRAPH
STATION
PLYMOUTH
Centre Hills
Soufriere Hill
South Soufriere
St. Georges Hill
Garibaldi Hill
Fox Bay
Bransby Pt.
Roche Bluff
Old Road Bluff
N.W. Bluff
I
II
III
IV
V
0
1
2
Scale of miles.

FIG. 11

evidence of this kind which is offered by the Wiechert records, in that the farther the suggested focus from the seismograph, the longer do recognizable earth movements persist. Taking into account all the available evidence, the suggested positions of the epicentres have been estimated and the results are shown in fig. 11. The small circles represent the epicentres of the earthquakes, the enclosed numbers corresponding to those given in Table I.

10—Estimation of the velocity of the waves

The considerations of the previous section suggest a method of estimating the velocity of the S waves in the surface rocks of Montserrat. Since we cannot expect the coefficient of reflexion of the waves at the various reflecting and refracting strata to be equal to unity, the simplifying assumptions indicated above will lead to an overestimate of the amplitude of the reflected wave motion arriving at any time after the arrival of the direct S wave. On the other hand, the wave motion at this later time may in part be due to waves of other type with a smaller velocity than that of the S waves, and these will contribute to the amplitude at that time. Ignoring these difficulties and knowing the position of the focus of the earthquake, the estimation of the velocity proceeds as follows: Let x_0 be the distance of the focus of an earthquake from the station in kilometres, and v the velocity, in km./sec., of the S waves. If the waves which are transmitted directly to the station arrive at a time t_0 sec. after the occurrence of the shock, then $t_0 = \frac{x_0}{v}$. Waves arriving at time $T = t_0 + t$ will have travelled a distance X given by $X = vT$. If we assume that the amplitude is inversely proportional to the distance from the focus, then there is a relationship between the amplitude A_0 at time t_0 and the amplitude A at time T given by the equation

$$\frac{A_0}{A} = \frac{X}{x_0} = \frac{t_0+t}{t_0} = 1 + t \cdot \frac{v}{x_0}.$$

In the record of any shock there are a number of movements at random times after the initial movement which stand out by their larger amplitude from the movements

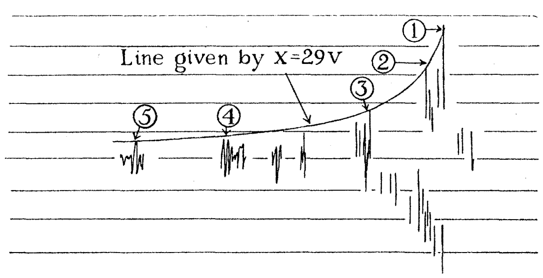

Fig. 12

constituting the "body" of the shock. In fig. 12 these movements for the distant shock No. D8, fig. 14, are indicated by arrows. The amplitude and the time of occurrence of these movements are measured. The quantities A_0/A for these movements are then plotted as a function of time. It will be seen from fig. 13 that in the case of this particular shock the points lie nearly on a straight line, and from the slope of this line it is deduced that $x_0 = 29v$. In the case of many of the more local shocks a similar relationship between A_0/A and t is found to hold, and graphs for a number of shocks are included in fig. 13. The numbers of the respective shocks for which these curves are drawn are shown in the figure and correspond with those given in Table I. By comparison with the positions of the suggested epicentres shown in fig. 11 it will be found that in general the nearer the suggested focus from the seismograph the smaller the constant k in the equation $\frac{A_0}{A} = 1 + \frac{t}{k}$ derived from the analysis of the record for that particular shock. Thus for the shocks Nos. 1 and 122, which are both grouped together in focal region I near the Grove, the values of k are 1·2 and 2·0 respectively, whereas for the more distant shocks Nos. 27 and 100, focal region II, the values are 4·1 and 5·3. The results are therefore in satisfactory agreement with those obtained by the first method.

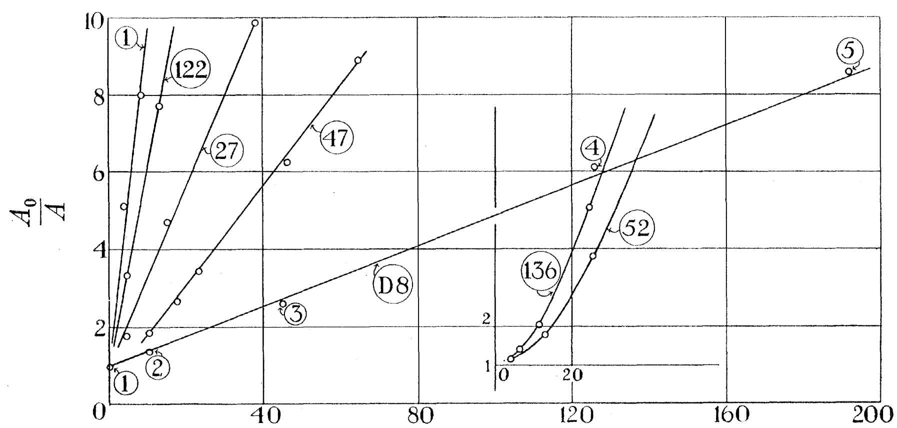

FIG. 13

In the case of a number of shocks, for example Nos. 52 and 136 (see fig. 13), the relation between A_0/A and t is not linear. This is more frequently true of shocks from focal region I than for the more distant shocks. It is perhaps to be expected that the relationship would be more likely to break down for the more local shocks, for it cannot be true at very small distances from the focus, since the equation suggests that the movements should become infinite for all shocks when $x = 0$. The method is very crude but it may be of some use in cases where better methods are not available for the determination of the position of foci.

The equation expressing the results for the distant shock No. D8 suggests that the amplitude would be infinite at a time $t = -29$ sec. If we assume that this time is identical with the moment of occurrence of the earthquake, then we can deduce the ratio of the velocities of the *P* and *S* waves. The ratio so calculated is 1·78.

If the position of the focus of any of the earthquakes in Montserrat can be determined, then it is possible to deduce absolute values for the velocities of the *S* waves. Taking several foci of which the position seems to be most clearly established by all the available evidence, the mean value is found to be 1·4 km./sec. for the *P* waves.

Summing up the conclusions of §§ 9 and 10 we can say that two primitive methods for the location of the earthquake foci have been developed. These show that the earthquakes have originated at a number of foci of which the epicentres lie in a broad belt running across the island in a north-easterly direction between the Centre Hills and the Soufrière Hills. This region thus shows evidence of both seismic and soufrière activity. Details of the positions of the active soufrières have been given by MacGregor (1937). It has been possible to recognize three principal "focal regions" which have given rise to a large proportion of these earthquakes. Whilst the position of the individual foci cannot be determined with precision, it is certain that the "focal region" which has given rise to the greatest number of earthquakes, during the time that seismographic observations have been in progress, is within 2 or 3 km. of the town of Plymouth. With the instruments now maintained in Montserrat it will be possible to recognize the occurrence of shocks at any of the old focal regions and to estimate the position of any new ones which become active.

11—Nature of the foci

It is of some interest to enquire as to the extent of the foci which, hitherto in the discussion, have been treated as point sources of waves. The very large variations in the amplitude distribution amongst the different stations for shocks which are known to be very local suggests that at least in many cases the focal regions are of small extent compared with the distance between stations. It would require a larger number of stations equipped with Jaggar shock recorders to decide this question definitely, but this view is in accord with the available information. In many cases the foci must be shallow in comparison with the distance between stations, for otherwise we should expect the amplitude at all stations to be approximately equal for all shocks. In some instances (see § 9) it was necessary to assume that the foci were less than 1 km. from the surface in order to explain the observed amplitude distribution.

12—Distant earthquakes

Since the establishment of the seismograph, twenty-two earthquakes have been recorded in Montserrat in which the *P*-*S* time separation is well developed so that accurate estimates of the *P*-*S* time intervals are possible. Reproductions of the records of four of these shocks are shown in fig. 14, and the details of all the shocks are given in Table II. It will be seen that shocks Nos. D, 1, 2, 4, 8, 10, 12, 14, 19 and 20 show a *P*-*S* separation of the same value within the accuracy of the measurements, suggesting that they originated at the same or closely neighbouring foci. Similarly with D, 5, 6, 7, 13 and 21. Of these distant shocks, the one of greatest intensity as recorded in Montserrat, that which occurred on 19 June, was also observed in Antigua and was described by the observer in that island in the following terms: "A slight tremor, with decreasing intensity, suddenly culminating in a sharp shock." No estimate was given of the time interval between the "tremor" and the "shock", but we may conclude from the description that the observer was perceiving the arrival of the *P* and *S* waves and that this shock was not immediately local to Antigua.

Table II—Details of shocks with measurable *P*-*S* time separation. Times are approximate local times only

	No.	Date	Time	Maximum amplitudes (mm.) Left	Right	*P*-*S* separation sec.
1936	D1	May 7	15.43	3·1	2·7	17·0
	D2	,, 9	12.40	2·9	2·8	17·3
	D3	,, 31	06.02	0·5	0·6	27·1
	D4	June 1	10.38	0·5	0·5	16·6
	D5	,, 3	19.13	0·6	0·4	11·4
	D6	,, 3	22.18	4·5	3·2	11·4
	D7	,, 5	14.32	1·2	2·0	11·5
	D8	,, 19	11.13	34·0	28·5	16·4
	D9	Sept. 11	22.00	1·9	1·4	21·5
	D10	,, 20	11.05	1·3	1·2	16·5
	D11	Oct. 31	16.00	9·6	5·8	6·2
1937	D12	Jan. 3	12.50	4·6	5·6	16·0
	D13	,, 14	12.40	3·3	4·9	11·4
	D14	,, 18	04.00	4·7	6·9	16·5
	D15	Feb. 12	21.00	4·6	3·5	6·6
	D16	,, 12	23.00	1·6	1·2	6·6
	D17	,, 13	21.00	1·5	?	6·6
	D18	,, 15	07.30	4·5	3·0	6·6
	D19	Apr. 29	09.20	6·3	5·4	16·0
	D20	May 21	04.30	1·8	1·3	16·3
	D21	,, 23	04.25	1·0	1·0	11·6
	D22	,, 27	22.30	4·5	5·0	73·6

The shocks Nos. D5 and D6 which occurred on 3 June give the same value for the *P*-*S* separation time. They were of very small amplitude as recorded in Montserrat, the maximum deflexions in the seismograph record being 0·6 and 4·5 mm. respectively, and such shocks would not be perceived with the unaided senses by an observer in Montserrat. These shocks were, however, so perceived in Antigua, and the shocks were described as coming from the direction of Montserrat. These facts taken together suggest that the common focus of these two earthquakes was under the sea between Montserrat and Antigua, and considerably nearer to Antigua than to Montserrat. If this interpretation is correct, we can make an estimate of the velocity, v_p and v_s using the value 1·78 for the ratio v_p/v_s. The value so found is 2·1 km./sec. for the P waves. This value depends on the assumption that the focus was 31 km. from Plymouth, the distance of St John's, Antigua, to Plymouth being 37 km. The value should be regarded as an upper limit.

13—General remarks on the earth movements

Hitherto, in discussing the results we have referred to the first shock and the main movement observed in the record of one of the local earthquakes as the P and S waves respectively. Do these wave motions correspond in actual fact to the waves similarly designated in the description of the seismograph record of a distant earthquake? There is no doubt that they do correspond to two different types of wave motion propagated with different speeds. Apart from the clear evidence provided by the "distant" shocks there is a general tendency for the duration of the fore shock to increase the farther the distance of the focus from the seismograph station in the case of the "local" shocks in Montserrat. But are what we have called the P waves longitudinal compressional movements similar in type to sound waves? Secondly, are the S waves transverse movements similar to those propagated through the body of the earth from the focus of an earthquake to a distant observing station or are they surface waves?

The restricted time scale of the Wiechert seismograph and the uncertainty as to the precise location of the foci makes it difficult to decide this question from the present results. In a few cases with local shocks it has been found possible to distinguish the direction and amplitude of the initial movement associated with the arrival of the P waves. The bearing deduced from these measurements can be compared with that given by the suggested position of the focus as found by the methods of § 9, and there is a reasonable degree of agreement between the results of the two methods. There is some evidence therefore that the P waves have been correctly identified.

Two empirical relationships which have been observed may be recorded here. The relative amplitudes of the P and S waves can be measured from the seismograph records of a number of shocks. This quantity varies widely in going from one shock to another, the extreme values found being 0·6 and less than 0·1. Secondly, if for a given shock the two components of the P and S waves can be distinguished and compared, it is generally found that the larger P component is associated with the smaller S component and vice versa. This second observation suggests that if the P waves are longitudinal in type then the S waves are transverse.

14—The earthquake of 10 November 1935

This important earthquake was observed at stations all over the world, and the position of the epicentre as deduced from the observations at seven stations of the

Jesuit Seismological Association was 18° 0′ N., 62° 8′ W. The estimated time of its occurrence makes it certain that it is to be identified with the earthquake which occurred in Montserrat on this date at approximately half past two in the afternoon, local time (4 hr. after Greenwich). It is evident that this earthquake was of critical importance for the general course of the seismic events which have taken place in Montserrat during the past 3 years. Up to the time of its occurrence the general tendency of the seismic phenomena had been to increase in intensity, and subsequently there was a marked decrease in the activity.

There is a marked contrast between the descriptions of the effects of this earthquake by observers situated at different points in Montserrat, and the accounts of other earthquakes which produced serious effects in the island at about the same time. The large earthquake of 10 November was particularly severe in the north end of the island and was responsible for serious damage to the church of St Peter's. It was of course felt all over Montserrat, but it was unusual in producing marked effects in other islands. At the time of the earthquake the Reverend H. R. Colton, of St Peter's, Montserrat, observed that severe landslides were taking place on Redonda, an island which is uninhabited at the present time, great clouds of dust rising into the sky and obscuring the island. The earthquake also caused some damage to the church at Basse-Terre, in the island of St Christopher, and to the cathedral of St John's, Antigua. On the other hand, according to the statement of the Hon. Mr H. Howes, this earthquake was not so severe at Gages as one which occurred on the following day, 11 November, an earthquake previously referred to which produced severe vertical accelerations at this point of which some of the effects are described in § 5.

The general disposition of the places mentioned in this section are shown in the map of the north end of the Leeward Islands reproduced in fig. 15. The descriptions of the effects of the earthquake on 10 November suggest that the epicentre was somewhere to the north of Montserrat, possibly near that of the so-called earthquake, No. D 8, which occurred on 19 June. The distribution of amplitude amongst the Jaggar stations produced by this latter shock is shown in fig. 10, and it will be seen that it is similar to the distribution which we should have expected to obtain for the severe earthquake of 10 November, on the basis of the descriptions of the local observers and of the distribution of damage in Montserrat. All the evidence therefore suggests that the severe earthquake of 10 November was much greater than any of the others which have occurred in Montserrat. Whereas the other earthquakes were for the most part highly local in their effects, and in this sense are properly described as volcanic earthquakes, the energy released in this earthquake was enormously greater than in any of the others. Whatever the agencies responsible for the general conditions of instability associated with the occurrence of the seismic phenomena, the decay in the activity following the earthquake suggests that its occurrence removed, at least temporarily, the dangerous stresses in the earth's crust in this region.

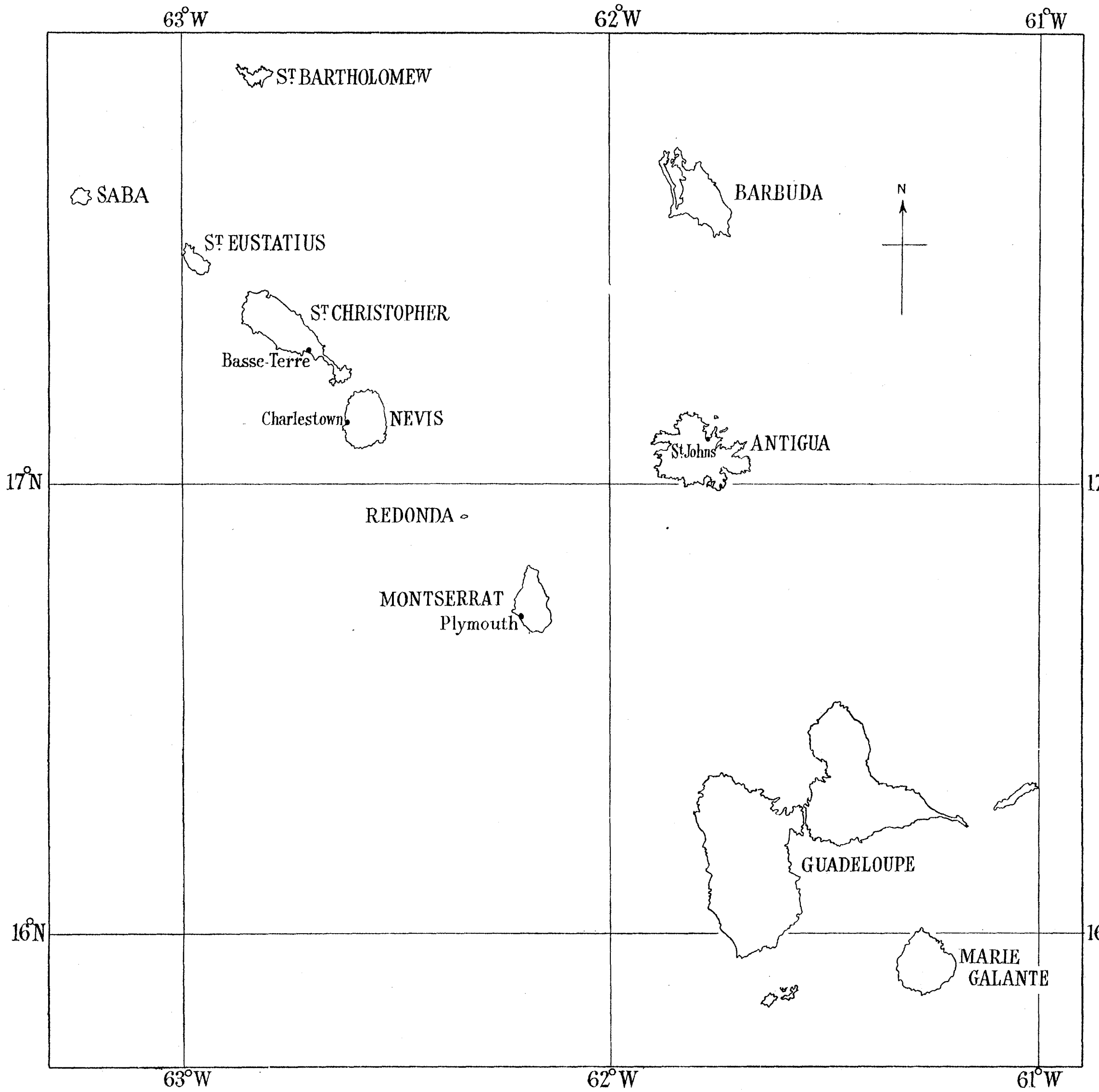

FIG. 15

15—GENERAL DISCUSSION

The more detailed analysis presented in this paper of the observations made in Montserrat has not led to any important changes in the general conclusions described in the preliminary report. For the sake of completeness these conclusions are included in the present paper.

a—Previous earthquakes in the Lesser Antilles

Unless there is a marked recurrence in the seismic activity in Montserrat, the history of the present episode will present many features in common with previous series of earthquakes in this region. Thus, according to the reports of residents, there

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were earthquakes in Nevis from February to June in 1930. The descriptions of observers and the distribution of the damage to buildings suggest that in this case also the shocks were local in origin, and none of the earthquakes appear to have been observed in the neighbouring island of St Christopher. The most disturbed regions were in the neighbourhood of Bath village, near Charlestown, where there are hot springs with sulphur deposits. Similarly, during the three years previous to the eruption of Mt Pelée and the Soufrière of St Vincent in May 1902, there was a series of earthquakes in Montserrat which ended at the time of the eruptions. The accounts of local residents in Montserrat suggest that in this instance the foci were not located immediately under the island. Mr Watson, for example, in his description of these earthquakes speaks of a warning tremor similar to that mentioned by Miss Gillie in connexion with earthquakes in Antigua, suggesting a fairly well-developed *P-S* separation. In the 12 months previous to the eruption of Mt Pelée in 1851 there were many earthquakes in Guadeloupe.

Thus although sequences of earthquakes in any island of the Lesser Antilles have not in general been followed by volcanic disturbance in that island, yet in several instances seismic disturbance at one point has been followed by volcanic disturbance elsewhere. The limited history of which we have record therefore suggests that the occurrence of earthquakes in large numbers should be regarded as evidence for the existence of unstable conditions in a common magma underlying the whole group which may or may not lead to volcanic disturbance at some point or points in the island chain.

b—Origin of the earthquakes

It has been shown from the observations made with the various seismographs that there are a number of focal regions under Montserrat at which a large proportion of the earthquakes have occurred. The fact that there are such large changes in the distribution of amplitude among the different stations suggests both that the foci of individual earthquakes are regions of limited extent and that they are in many instances close to the surface of the earth compared with the distance between stations, i.e. within 1 or 2 km. of the surface. Otherwise, if the foci were all deep seated, we should expect to find the amplitude for all stations nearly equal for all shocks. These conclusions are strengthened by the fact that in estimating the position of the foci it has been necessary in some instances to assume that the distribution in amplitude is affected markedly by certain surface features (cf. § 9).

In some volcanic regions, notably in Hawaii, earthquakes occur most frequently when magma is falling in the volcanic crater. On the other hand, the history of events in the Lesser Antilles suggests that earthquakes occur most frequently in this region at times of increasing magmatic pressure. The fact that seismic activity has, in some instances, terminated with the occurrence of a volcanic eruption is then to be regarded as a consequence of the release of magmatic pressure. It is possible that such a release of pressure was brought about in the neighbourhood of Montserrat by the occurrence of the severe earthquake of 10 November 1935.

The most plausible explanation of the local earthquakes in Montserrat is therefore that they are due to magmatic intrusion. Such a view accounts for the fact that the disturbed regions are very restricted in area and offers a simple explanation of the very sharp vertical accelerations which the shocks sometimes produce. One can imagine that the shocks are produced by a kind of "hammer" blow produced when the magma, breaking through a barrier which it has weakened by its action during times of increasing magmatic pressure, is suddenly brought to rest by the opposition of a new barrier.

At a certain stage in the history of a volcano in this region it is possible that such intrusive processes may lead to a general strengthening of the volcanic edifice by a kind of grouting process, so that subsequently the volcano is better able to resist the incidence of magmatic pressure. Such effects would explain the existence in the restricted area presented by the island of Montserrat of as many as six old volcanoes. At any stage in the history of the island, the volcano most recently active must have represented the region least able to withstand magmatic pressure. Subsequently a new volcano has broken out at a point which previously was stronger than the edifice of the first volcano. This sequence of events must have occurred at least five times in the geological history of the island, so that it is certain that the volcanic edifice does eventually grow in strength relative to the surrounding country.

16—Conclusions

Whilst speculations of the kind made in the previous section are of interest, the information which has been obtained during the course of the expedition has not been sufficient to enable us to make any predictions as to the likelihood or otherwise of the present earthquakes being followed in the near future by a volcanic event in Montserrat or elsewhere. Such predictions can only legitimately be made on the basis of a real understanding of the complex of interacting processes and conditions which together determine the course of such events. On the basis of the information which has been accumulated, however, I am of the opinion that the continued decline in the seismic activity and the simultaneous decrease in the rate of emission of gas from the Gages soufrière following the severe earthquake of 10 November 1935 suggest that the seismo-volcanic episode which has occurred in Montserrat in the past few years is now drawing to a close. The results strongly suggest that the dangerous strains in the earth's crust in this region were relieved at least temporarily by the occurrence of this earthquake.

These facts should not, however, be allowed to lead to a too easy optimism. On several occasions in the past, scientific expeditions have been made to the scene of disasters in these islands and reassuring reports have subsequently been issued on the basis of insufficient knowledge, with serious consequences. The earth's crust in these regions should be regarded as a very delicately balanced structure, and a knowledge of those factors which determine its history will only be obtained by long-continued observations at a number of points in the island chain. The magnitude of the disasters which have occurred in the past in these regions makes it desirable that these observations should be initiated without delay. It is very likely that the best fruits of such observations will not be seen for many years, but eventually they may be responsible for saving many hundreds of lives, and it is certain that observations even on a modest scale will give results of great interest to geophysics.

The seismograph which has been established in Montserrat can be regarded as a first step in the establishment of such observations in one island. This could be followed in the near future by similar observations in other islands. I would suggest that in the first instance some form of seismograph could be established in the islands of Antigua, St Christopher, Nevis, and St Vincent. These instruments could take the form in the first instance of Jaggar shock recorders, each with a clockwork mechanism so arranged that the chart needs to be changed only once in 2 days. It would be an advantage if the magnification of such instruments were greater than that described in this paper, say 80 instead of 20 (see Appendix). Subsequently this instrument might be replaced by a seismograph with larger amplification and longer natural period, so that it would record distant shocks and any relatively local shocks in greater detail.

A great advantage of having established centres of seismographic observation in the Leeward and Windward Islands would lie in the fact that it would be possible to begin observations of any seismic activity in any one of the islands, of a similar character to that which has taken place in Montserrat in the past few years, at a much earlier date in the history of the episode than has been possible in the recent instance. Had the instruments been established in Montserrat 12 months earlier than was actually the case, a great wealth of observations would have been made available. Jaggar shock recorders could be quickly, and at relatively small expense, transported from one island to the island nearest to the centre of the disturbance.

It is a great pleasure to acknowledge my indebtness to Sir Gerald Lenox-Conyngham for much advice and assistance both in Montserrat and during the passage home; to Dr T. A. Jaggar and Mr A. G. MacGregor for the advantage of many conversations with them during our residence in Montserrat; to Mr F. A. Perret who kindly allowed me to erect a shock recorder in his hut at the Gages soufrière and who gave me the benefit of his great experience of these islands during his visit to Montserrat from 16th to 19th May 1936, and finally to the many friends who undertook the maintenance of various instruments and who made our stay in Montserrat so pleasant.

It was possible for me to join the expedition through the kindness of the authorities of the University of Bristol, who granted me leave of absence.

Summary

1—An investigation has been made of the earthquakes which occurred in Montserrat after the arrival of the members of the expedition in March 1936, and of the rate of emission of gases from the Gages soufrière.*

2—The variation of the seismic activity with time has been studied and an attempt has been made to determine the position of the foci of the various earthquakes. For the latter purpose two methods have been developed: The first depends on measuring the amplitude of the horizontal movements produced by the various shocks at a number of points distributed throughout the island. The second method depends on the fact that the earth movements following the first arrival of the shock at any station die away more rapidly the closer the focus to the observing station. This decay in the amplitude of the earth movements with time has been analysed algebraically, and from the results the relative distances of the different foci from the station can be estimated. The two methods give results which are in reasonable agreement with one another. An estimate has been made of the velocity of the earth waves in the surface rocks of Montserrat. Two types of wave motion are prominent in the records of the shocks, and these have been identified provisionally as the P and S waves of conventional seismology. Estimates of the velocity of the P waves vary from 1·45 to 2·15 km./sec. and of the S waves from 0·8 to 1·2 km./sec.

3—A number of residents in Montserrat have given accounts of the earthquakes which occurred before the arrival of the expedition, and complete records are available of the number of shocks occurring daily for the whole of the period from May 1934 to the present day.

4—The general tendency of the seismic activity was to increase until the time of the serious earthquakes of 10 and 11 November 1935, following which there was a marked decline. Of the earthquakes which have occurred during the whole of the present period in Montserrat the only one which was great in the sense of being recorded at seismograph stations all over the world was that of 10 November 1935 at 18 hr. 28 min. G.M.T. The focus of this earthquake was not under the island but was probably several miles to the north in the neighbourhood of Redonda. It is likely that the release of energy which accompanied this earthquake was of a different order of magnitude from that in any other individual earthquake in this region during the past 3 years.

5—Of the earthquakes which occurred in Montserrat during the time of residence of members of the expedition the great majority originated under the island. A large proportion of the shocks arose from three "focal regions", the most important of which is within 1 or 2 km. of the town of Plymouth. There is a belt running across the

* For an account of the work on the emission of gases from the soufrières, see Powell (1937).

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island in a north-easterly direction between the Centre Hills and the Soufrière Hills which shows both seismic and soufrière activity.

6—Taking all the available evidence into consideration it is possible to make reasonable speculations as to the origin of the earthquakes. It is suggested tentatively that they are due to intrusive processes taking place under the island during a time of increasing magmatic pressure.

7—The continued decline in the seismic activity and the reduction in the rate of emission of gases which has followed the severe earthquake of 10 November 1935 suggest that the seismic-volcanic episode which has been taking place in Montserrat in the last 3 years is now drawing to a close. This decline may be due to a decrease in the general magmatic pressure as a consequence of this earthquake. On some previous occasions in this region release of pressure has been achieved by volcanic action.

8—It is important that the decline in the seismic activity, whilst reassuring, should not be allowed to lead to an easy optimism. Predictions as to the likelihood of the seismic events in Montserrat being followed in the near future by a volcanic event in Montserrat or elsewhere could only legitimately be made on a basis of a real knowledge of the complex of interacting processes which together determine the course of such events. At present our knowledge is rudimentary and quite inadequate to form the basis for such predictions. What is certain is that the geological history of these islands is not complete, and that crises are liable to occur in the indefinite future.

9—The knowledge necessary for a real understanding of the underlying process responsible for the volcanic and seismic phenomena in these regions will only be obtained by long-continued observations at a number of points in the Lesser Antilles. It would be of great advantage if these observations, even on a modest scale, could be inaugurated without delay. The advantages of making organized observations may not be seen for many years, but eventually they may lead to the saving of many lives.

Appendix

From the experience gained during the course of the expedition it is possible to give an appraisal of the performance of the various instruments which may be of value for future work either in Montserrat or in other places.

a—The Wiechert seismograph

This instrument has given considerably more information than any other individual instrument as a result of its much larger magnification and the fact that it registers two components. For the specific problems to be met in investigating highly local shocks it would have been a great advantage to have a more extended time scale, and this could be obtained by simple changes in the recording mechanism. The screw which provides the lateral motion to the drum carrying the cylinder of smoked paper could be given a smaller pitch, so that the distance between the successive lines drawn by the pens is reduced. The speed of rotation of this drum could then be increased say fourfold by alterations in the governor mechanism, without making it necessary to change the charts more than once in 24 hr., the normal period. Especially if this instrument were adjusted to a relatively low period to be insensitive to changes in tilt, this modification would introduce no confusion owing to overlapping of successive lines, and for the local shocks the low period is of no consequence. With the instrument so adjusted a temporary site on a shallow foundation is adequate. It is difficult to make the instrument give first class registration of both distant and local shocks. For distant shocks the pens must be very accurately balanced to reduce frictional constraints to a minimum. In this condition, the period of oscillation of the pen in its stirrup in a vertical plane is of the order of seconds. For local shocks the vertical impulses associated with them sometimes tend to raise the pens off the paper and part of the horizontal movements are thus not recorded (see fig. 14, shock D8, and fig. 7, shocks 82 and 104). For the recording of local shocks only, frictional constraints are much less important and the pens need not be so delicately balanced.

b—The Jaggar shock-recorders

The performance of these instruments has proved very satisfactory. The stationary mass seems to have been considerably greater than that used previously and has a number of advantages. It enables a steady zero to be obtained with periods which are relatively long for this class of instrument, and the increased inertia makes it easy to introduce further magnification by lever systems if such is desired without serious constraints arising as a result of friction between the pen and the paper.

The clockwork system provided by Dr Jaggar in which the separation between the successive lines of the spiral is much reduced enables a considerably extended time scale to be provided and no confusion is introduced by the closeness of the lines. This type of recording could be very usefully employed in an instrument with the more normal time scale so that the chart needed to be changed only once in 4 days, thus giving a considerable saving in labour and in general running expenses.

It is perhaps worth noting that in cases where instruments are to be sent to distant places some saving can be made by sending out only the essential metal parts, clock, etc., of the instruments and allowing the cases of the instruments to be made locally. In the West Indies the local cabinet makers can undertake this work, and this plan enables the cost of packing and transport to be reduced.

c—The sound-ranging equipment

It was unfortunate from a purely technical point of view that it was not found possible to test the usefulness of the sound-ranging equipment. The most important problem to be met in connexion with this instrument is that of reducing the running costs. The best method of approach might be to construct an instrument with a "memory". The problem of translating the earth movements into electrical impulses can be solved in many simple ways. If these electrical impulses are made to magnetize a wire which subsequently leads to the photographic registration of the impulses, in the manner of the Blattner process, then the cost of photographic paper could be made negligible, since the instrument need only record during the 1 or 2 min. following the passage of a shock.

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Jaggar, T. A. 1932 "The Volcano Letter", 14 Jan.
Jeffreys, H. 1927 *Mon. Not. R. Astr. Soc.* Geoph. Suppl. **1**, 334–44 and 400.
— 1935 *Proc. Phys. Soc.* **47**, 455–8.
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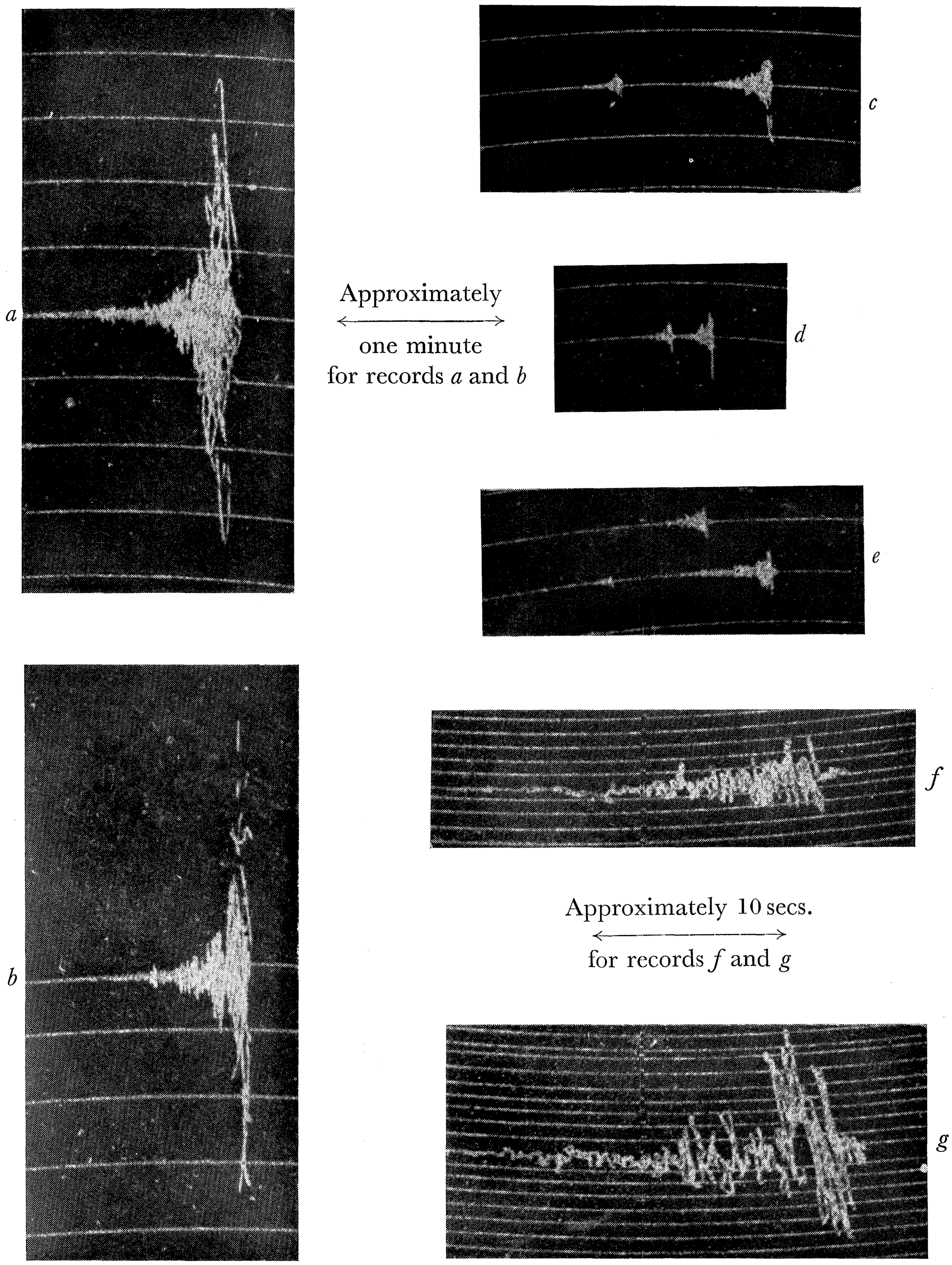
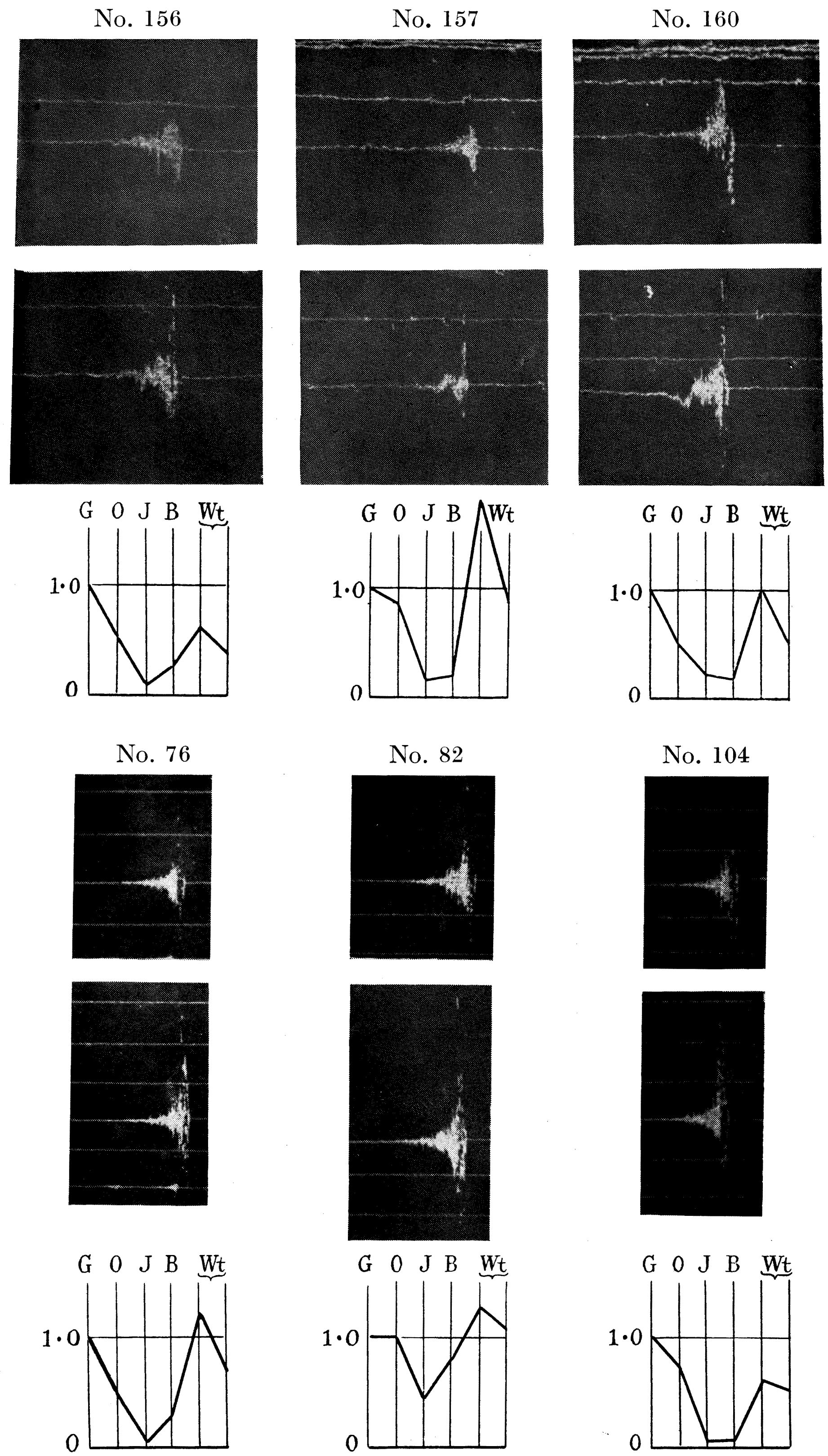
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



Records *a* to *e* are taken with instrument in which chart makes one revolution per hour. *f* and *g* with instrument making one revolution in ten minutes. *f* and *g* shew *P* and *S* waves clearly resolved.

FIG. 4—Examples of records from Jaggar shock recorders about four times natural size.



These foci are near Gages, Grove and Olveston. There are large changes in the relative amplitudes at the three stations. The interval between time marks on the records is one minute.

Fig. 7—Records obtained with the Wiechert seismograph. Shocks from focal region I.

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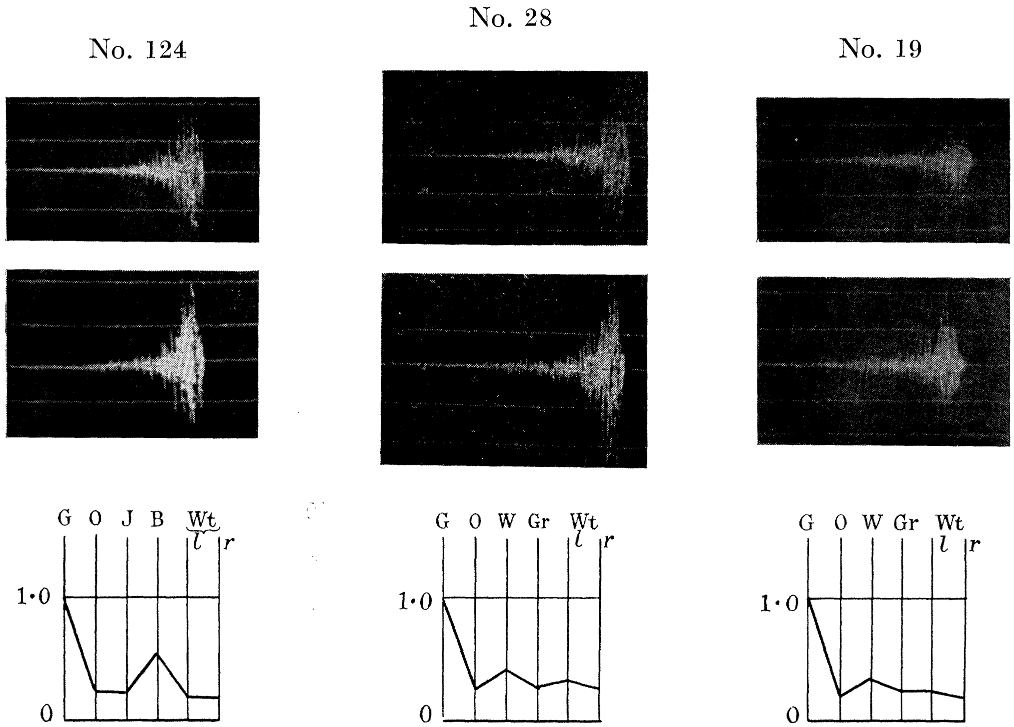
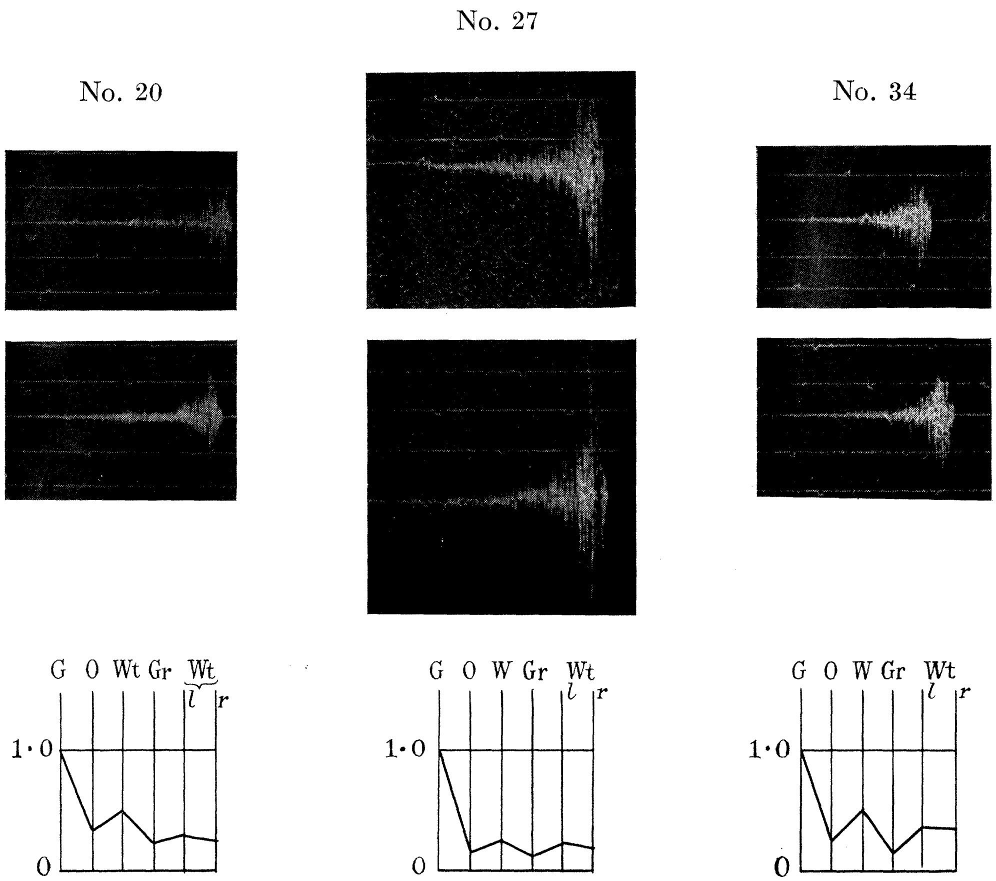
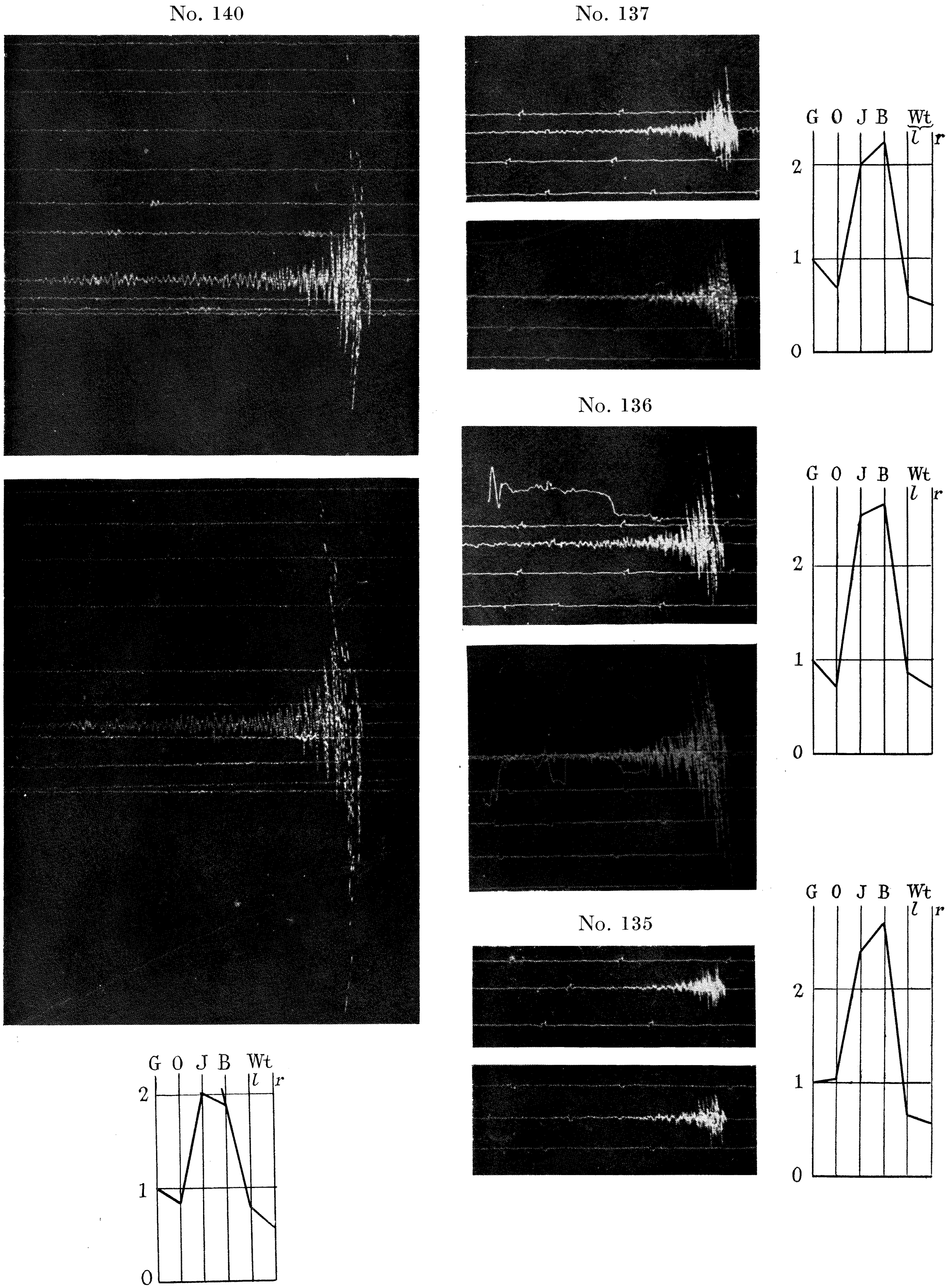


Note that the distribution of stations is different for shock No. 124 from that for the other shocks in this figure.



The interval between time marks on the records is one minute.

FIG. 8—Shocks from focal region II.



These shocks arise from relatively distant foci and the two amplitudes as recorded on the seismograph are approximately equal. The interval between time marks on the records is one minute.

Fig. 9—Shocks from focal region III.

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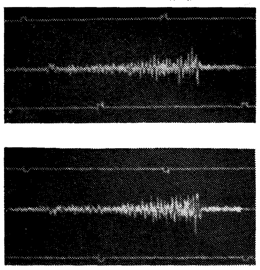
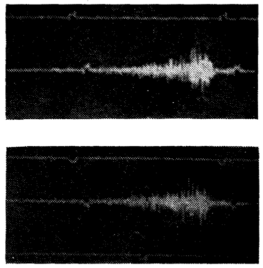
D 2



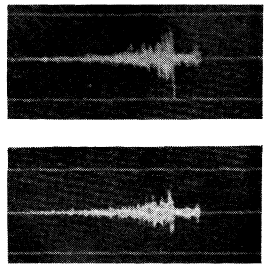
P–S, 17·6 secs.

D 1



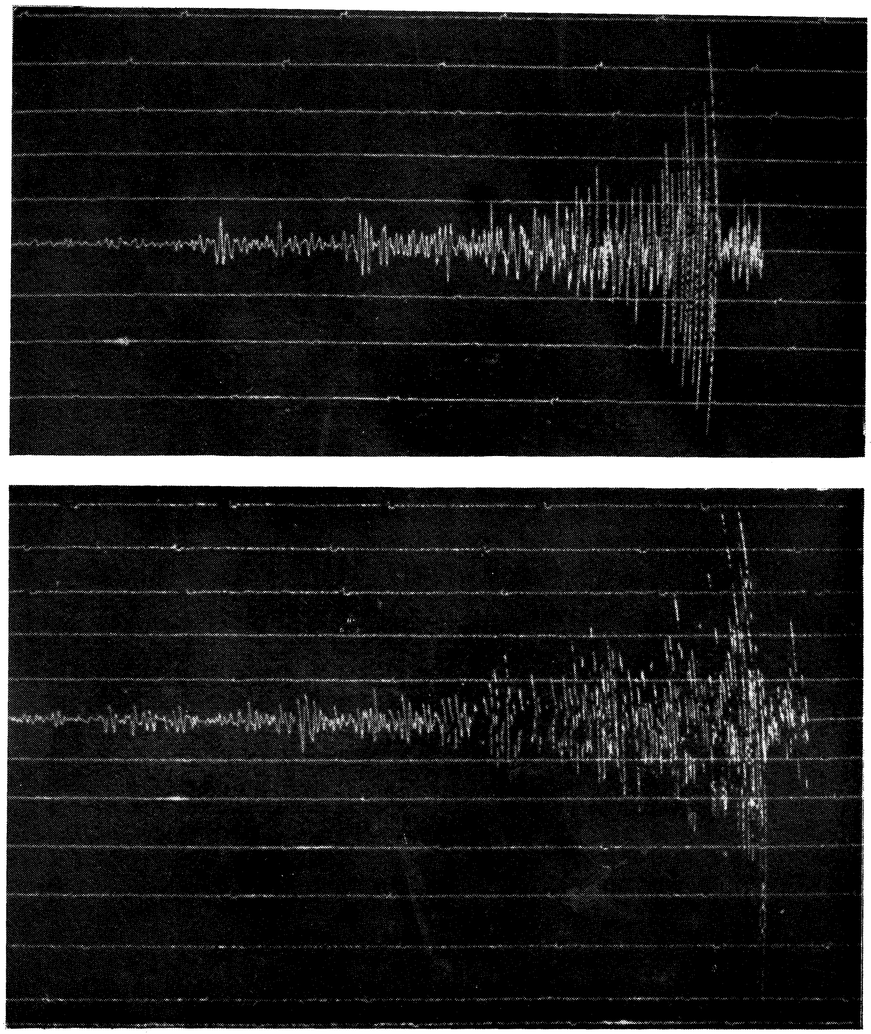
P–S, 17·0 secs. (?)

D 6



P–S, 11·4 secs.

D 8

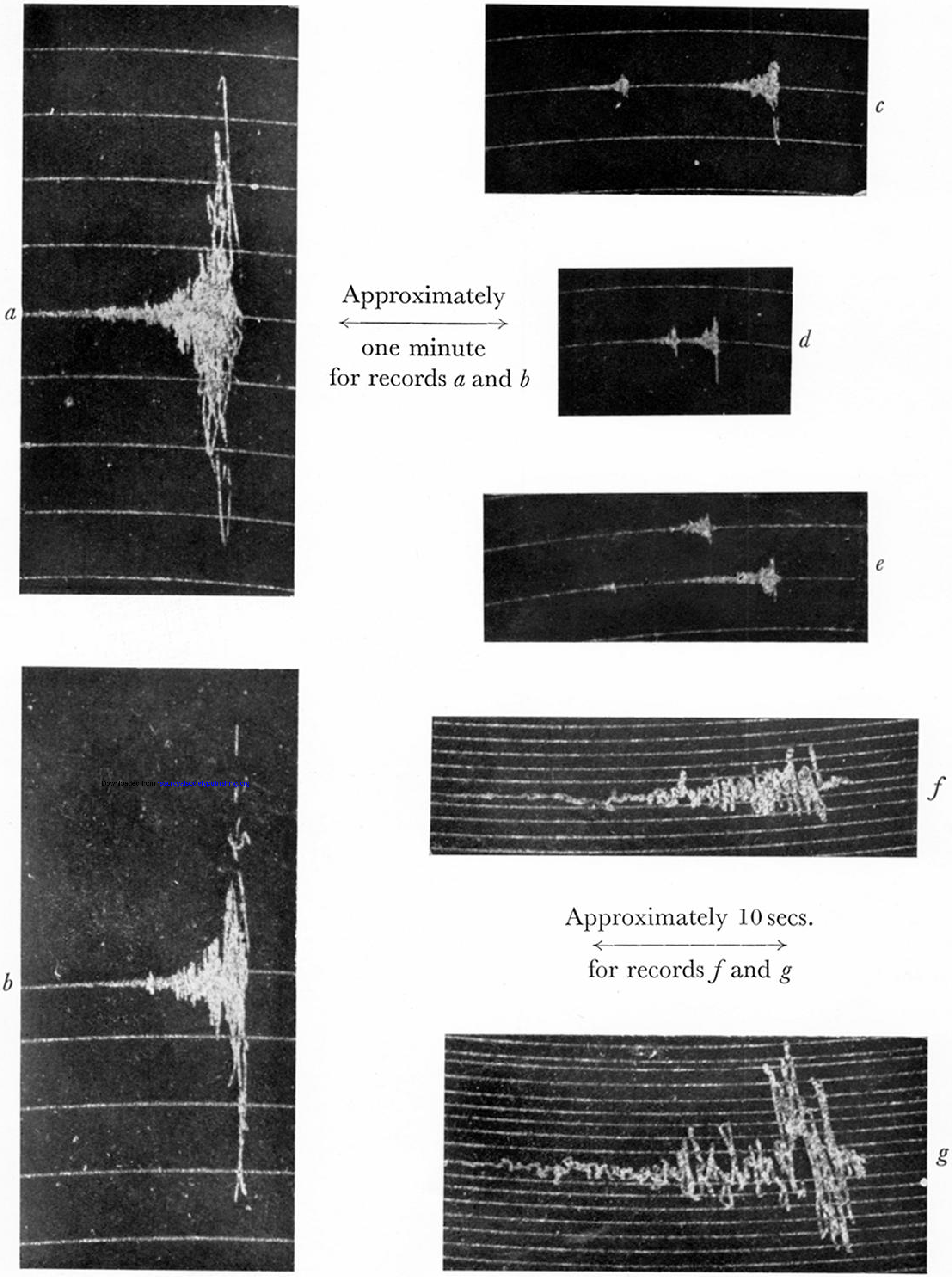


P–S, 16·4 secs.

The interval between time marks on the records is one minute.

FIG. 14

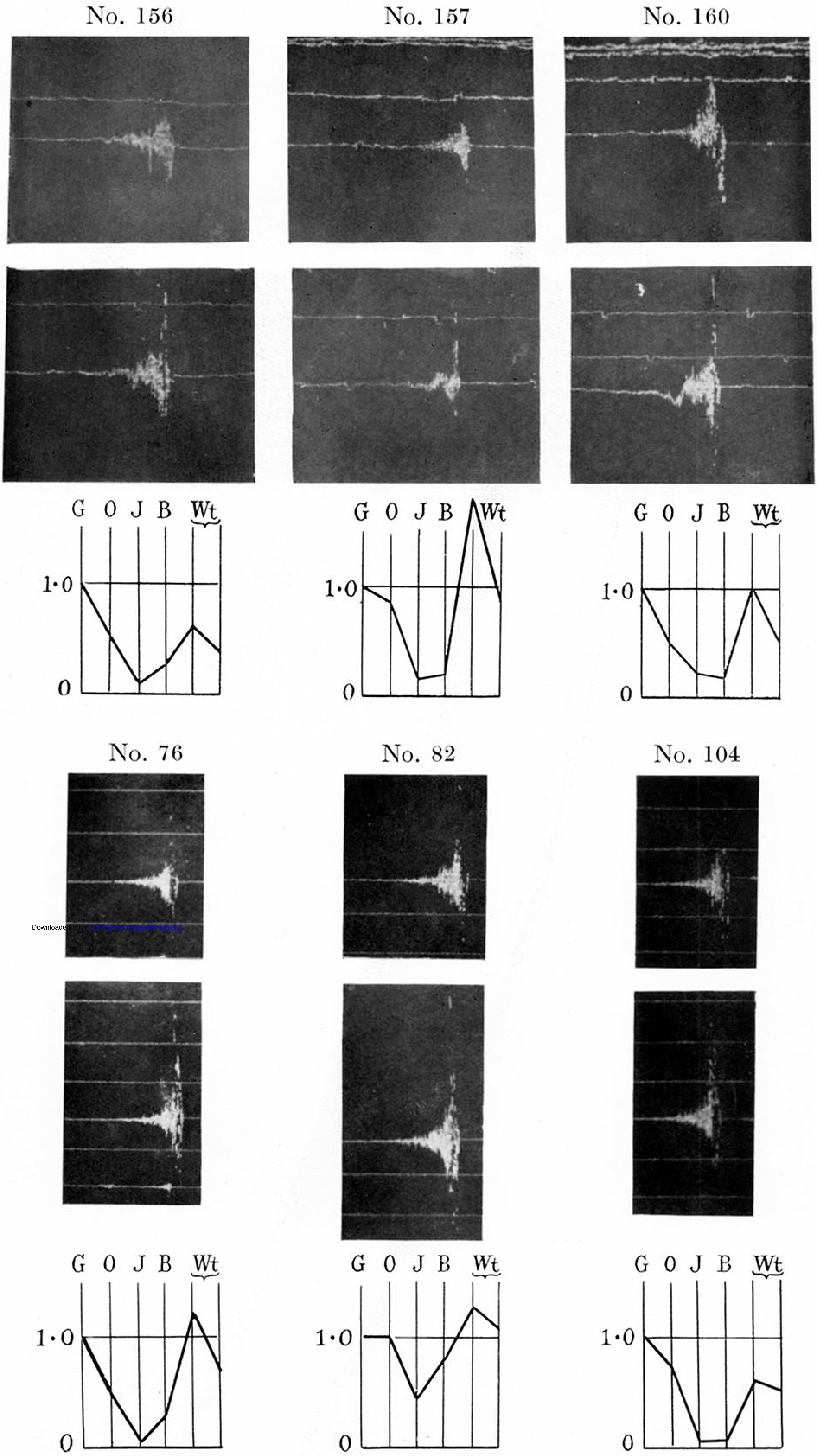
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



Records *a* to *e* are taken with instrument in which chart makes one revolution per hour. *f* and *g* with instrument making one revolution in ten minutes. *f* and *g* shew *P* and *S* waves clearly resolved.

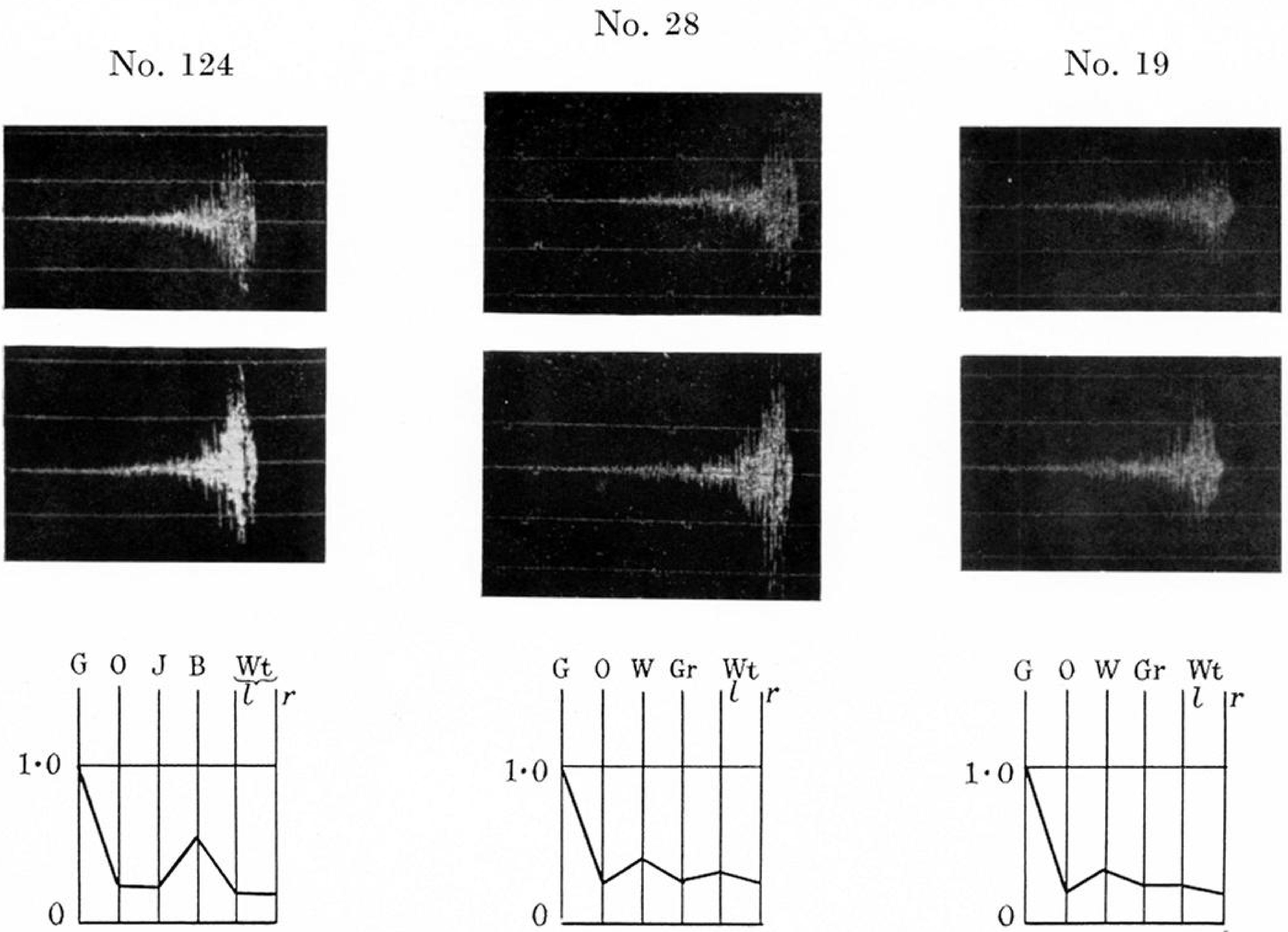
FIG. 4—Examples of records from Jaggar shock recorders about four times natural size.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

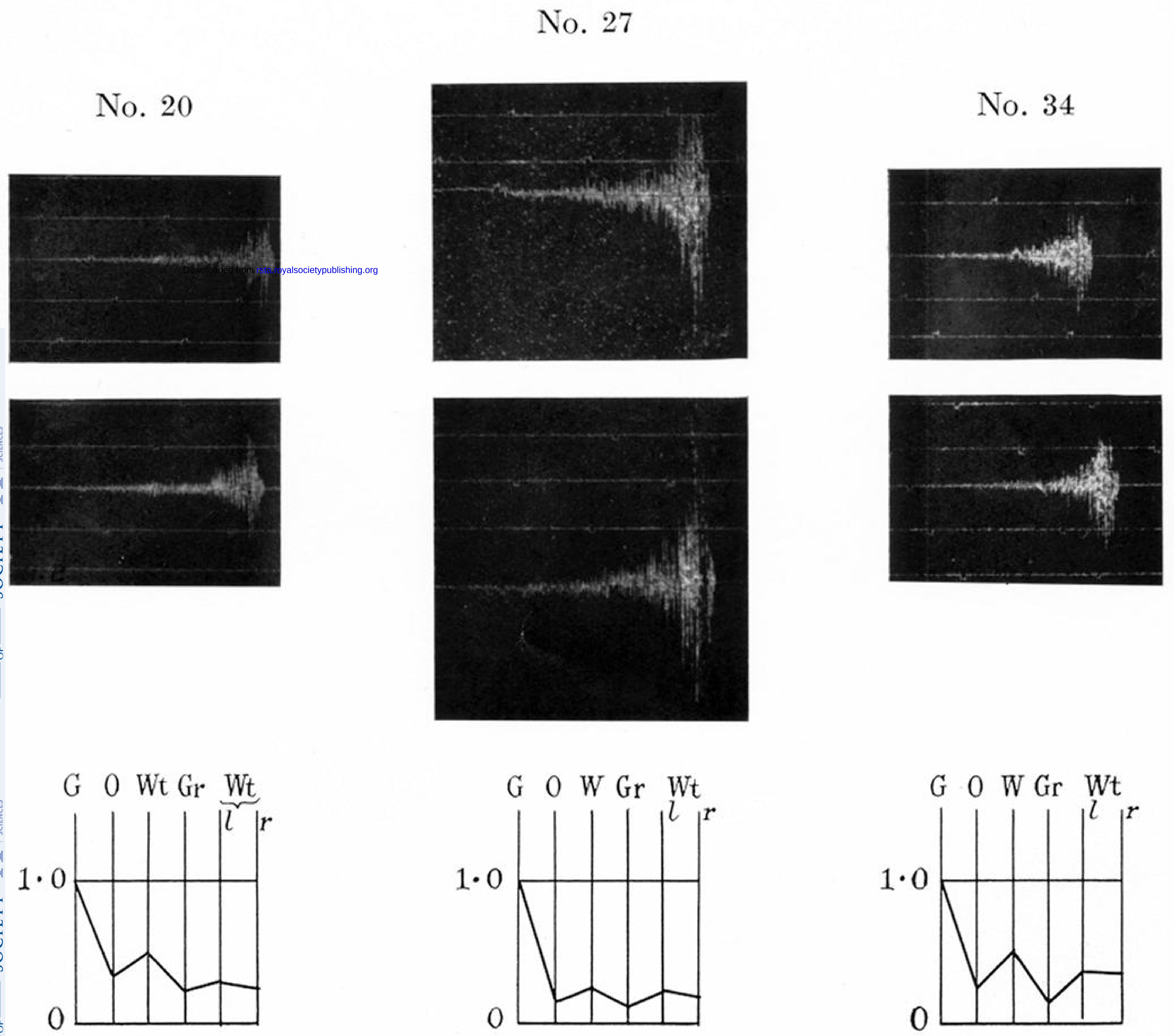


These foci are near Gages, Grove and Olveston. There are large changes in the relative amplitudes at the three stations. The interval between time marks on the records is one minute.

FIG. 7—Records obtained with the Wiechert seismograph. Shocks from focal region I.



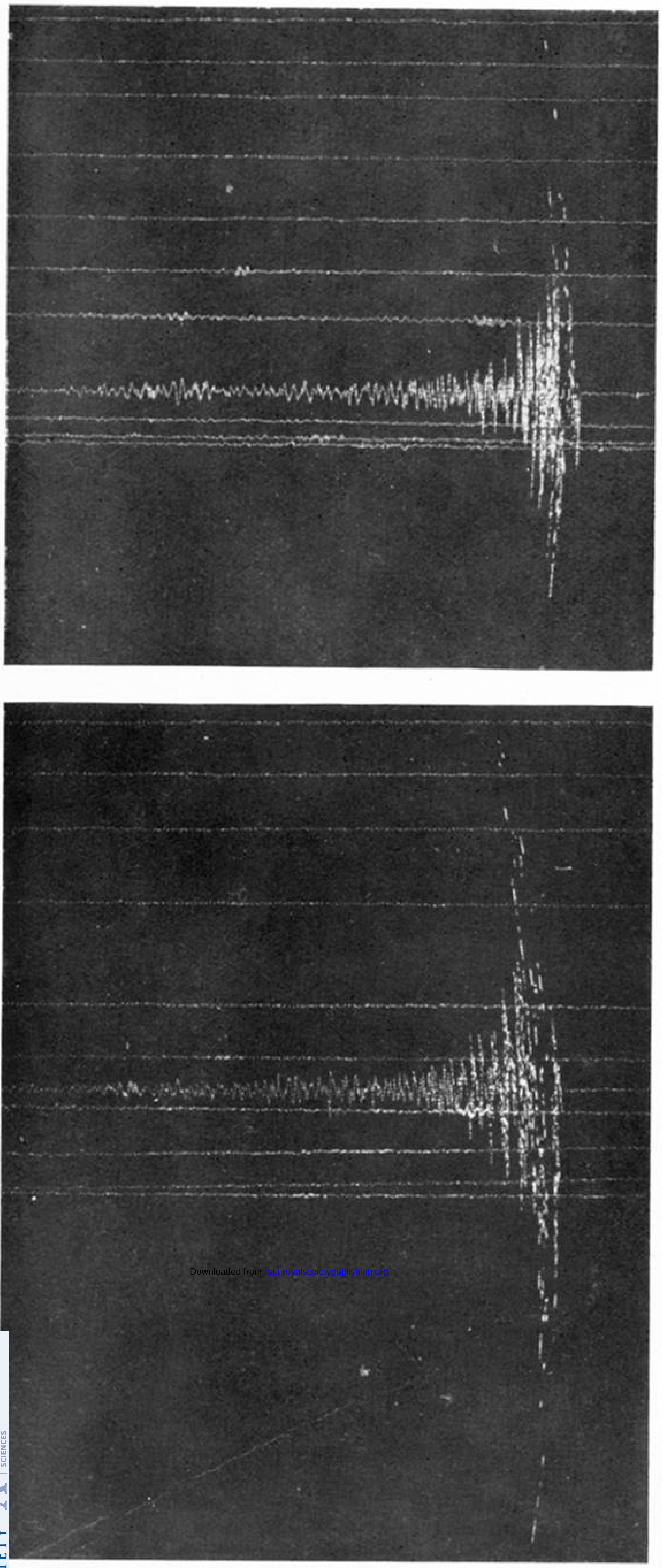
Note that the distribution of stations is different for shock No. 124 from that for the other shocks in this figure.

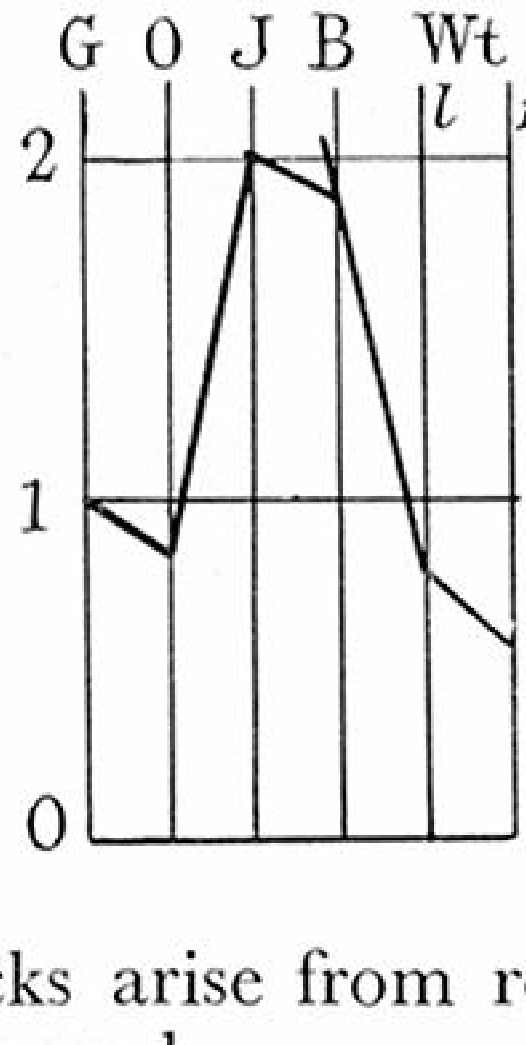


The interval between time marks on the records is one minute.

FIG. 8—Shocks from focal region II.

No. 140





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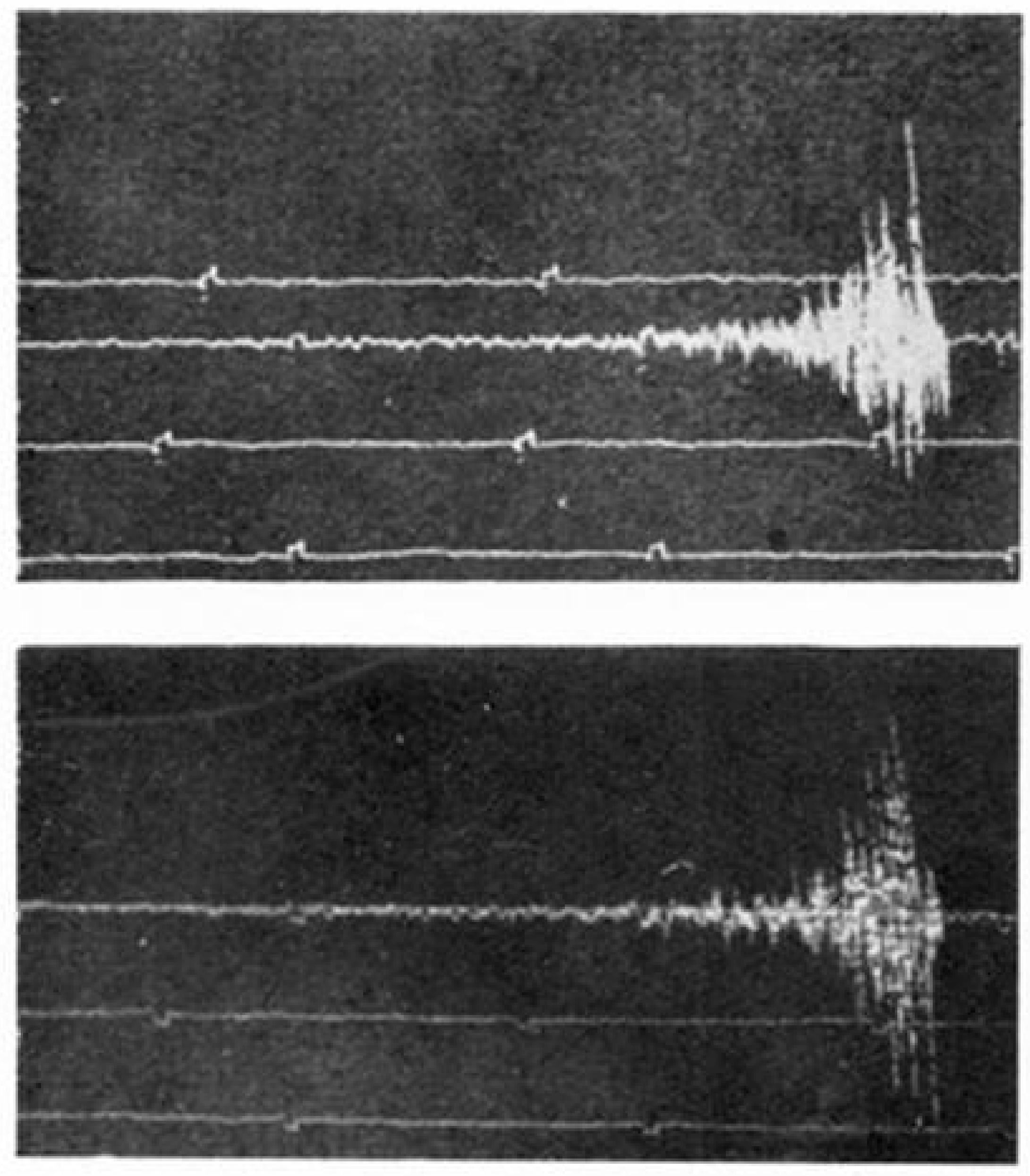

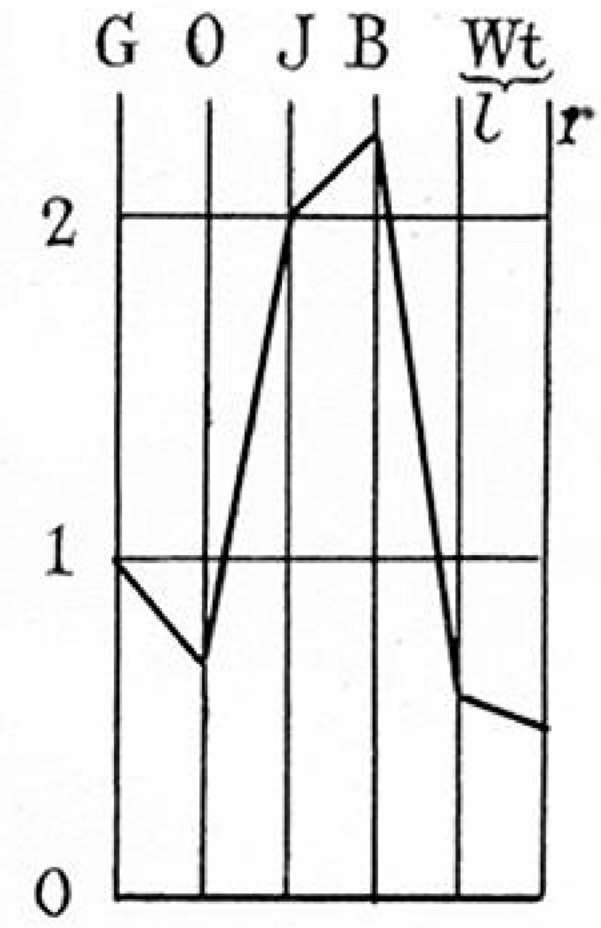

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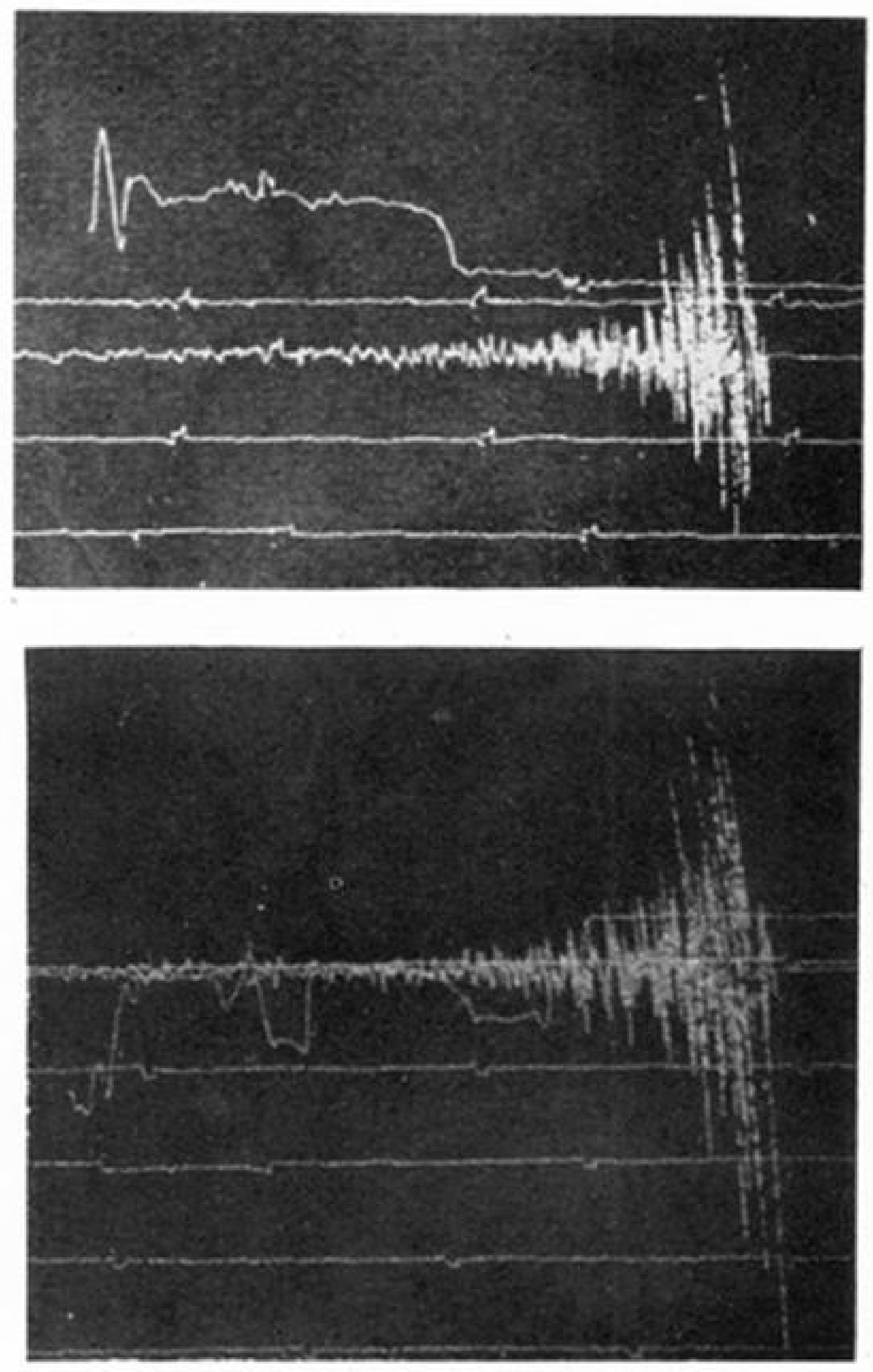

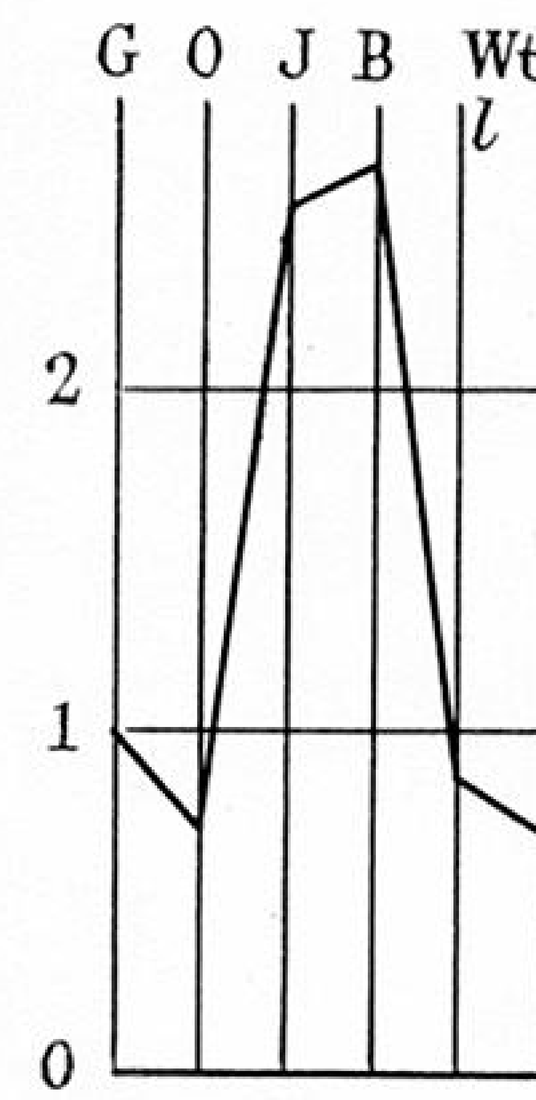

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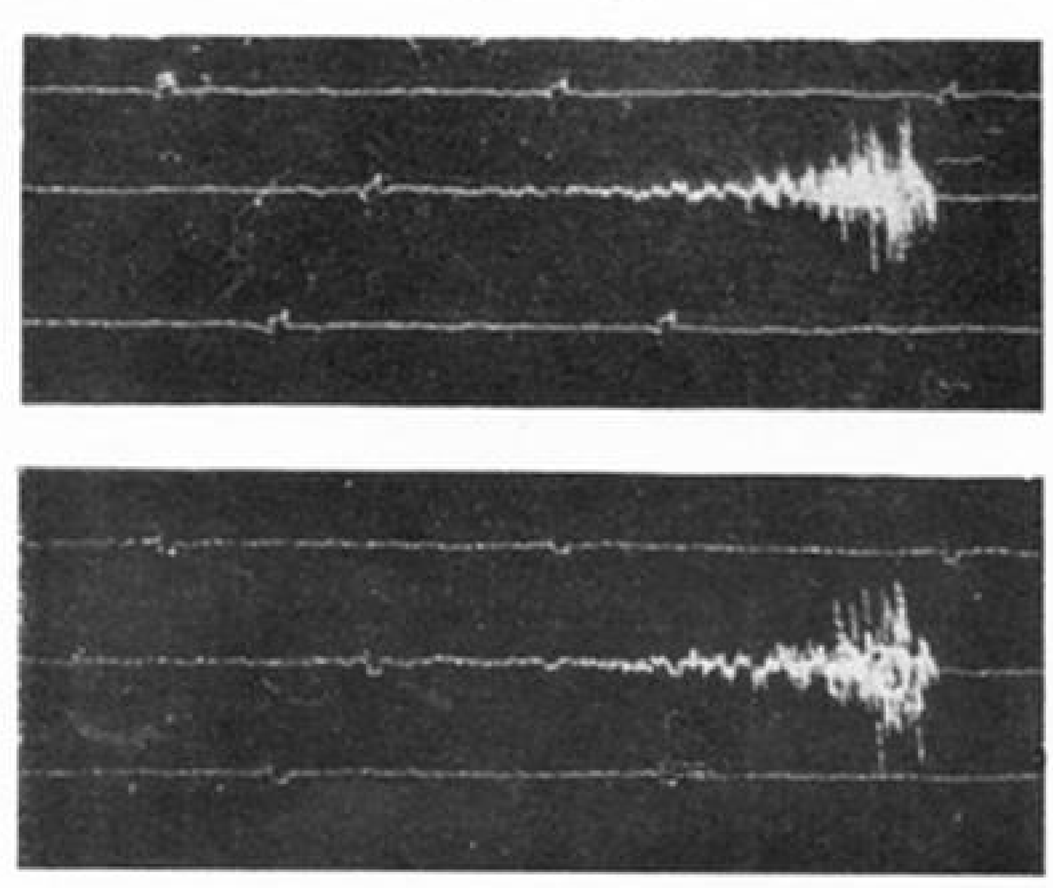
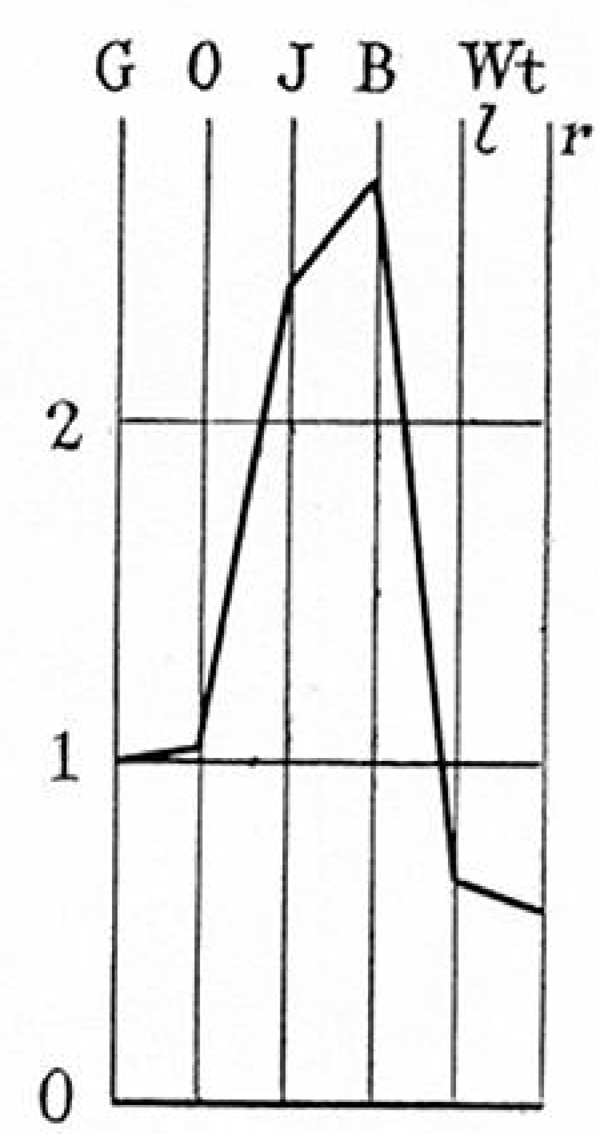
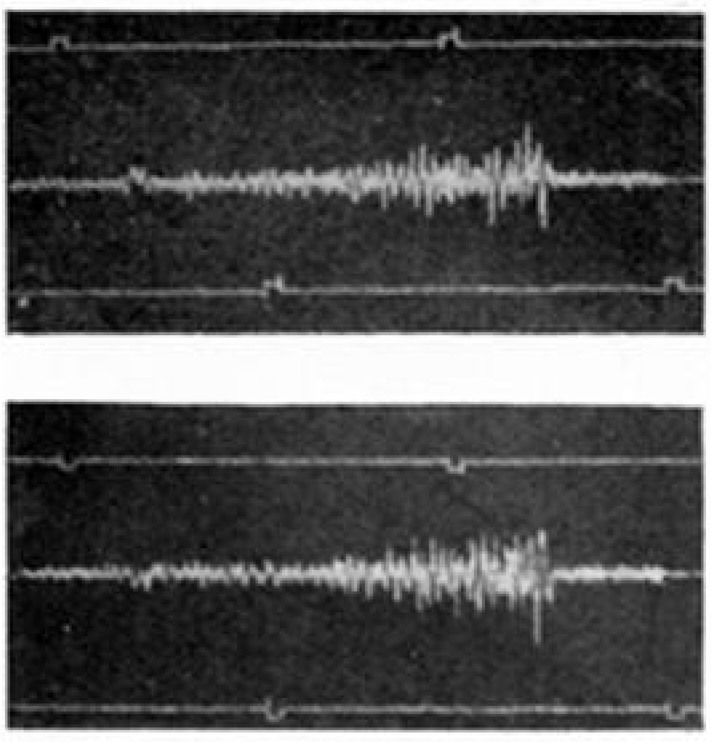




These shocks arise from relatively distant foci and the two amplitudes as recorded on the seismograph are approximately equal. The interval between time marks on the records is one minute.

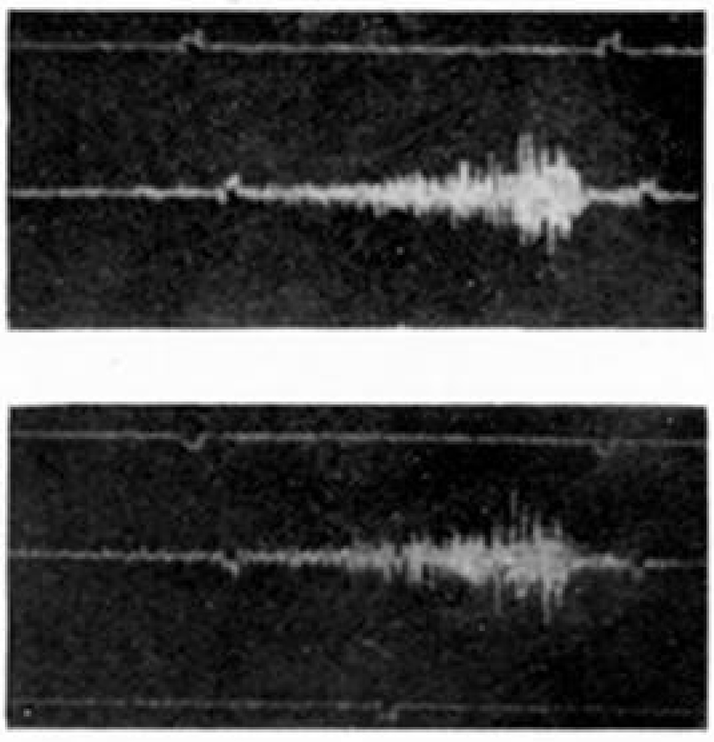
FIG. 9—Shocks from focal region III.

D 2



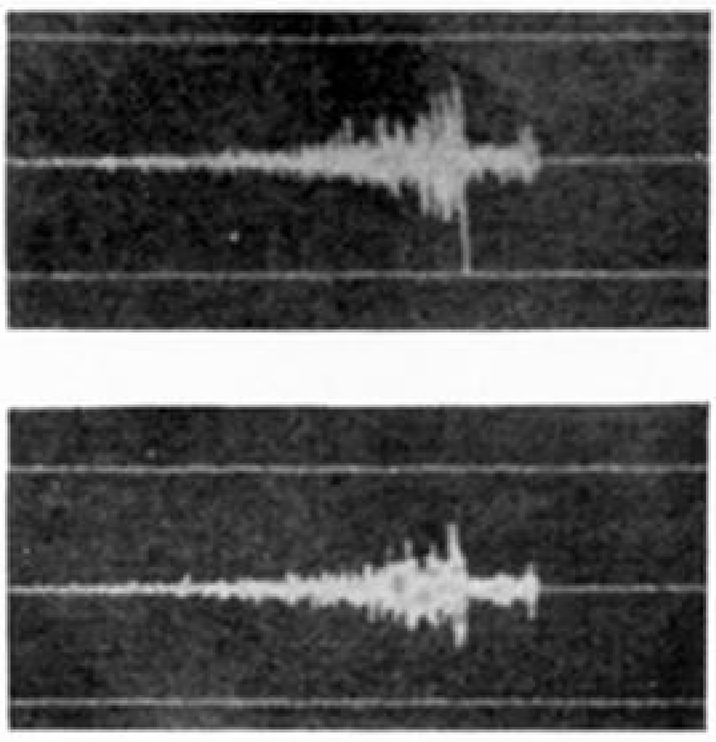
P–S, 17·6 secs.

D 1



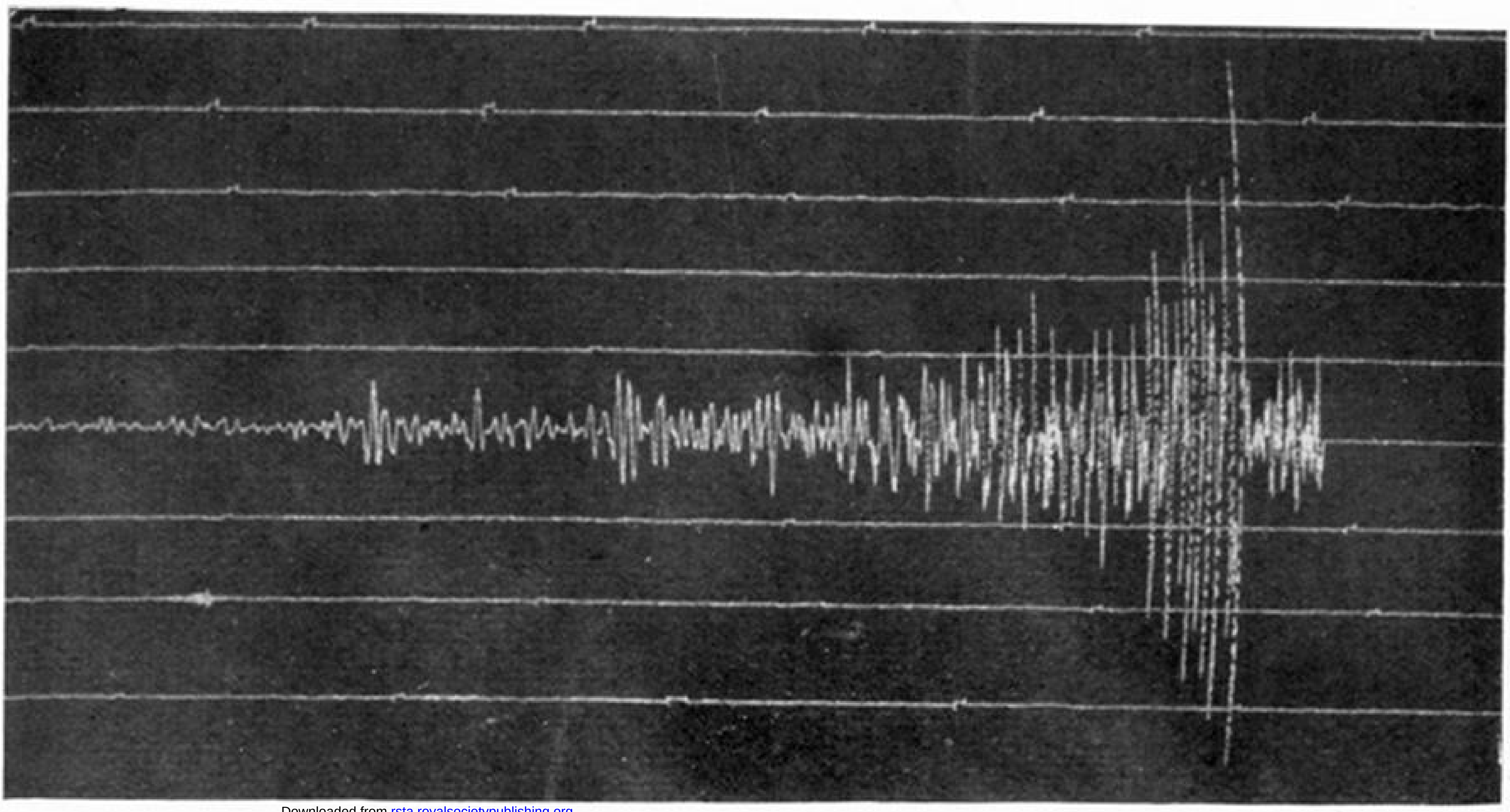
P–S, 17·0 secs. (?)

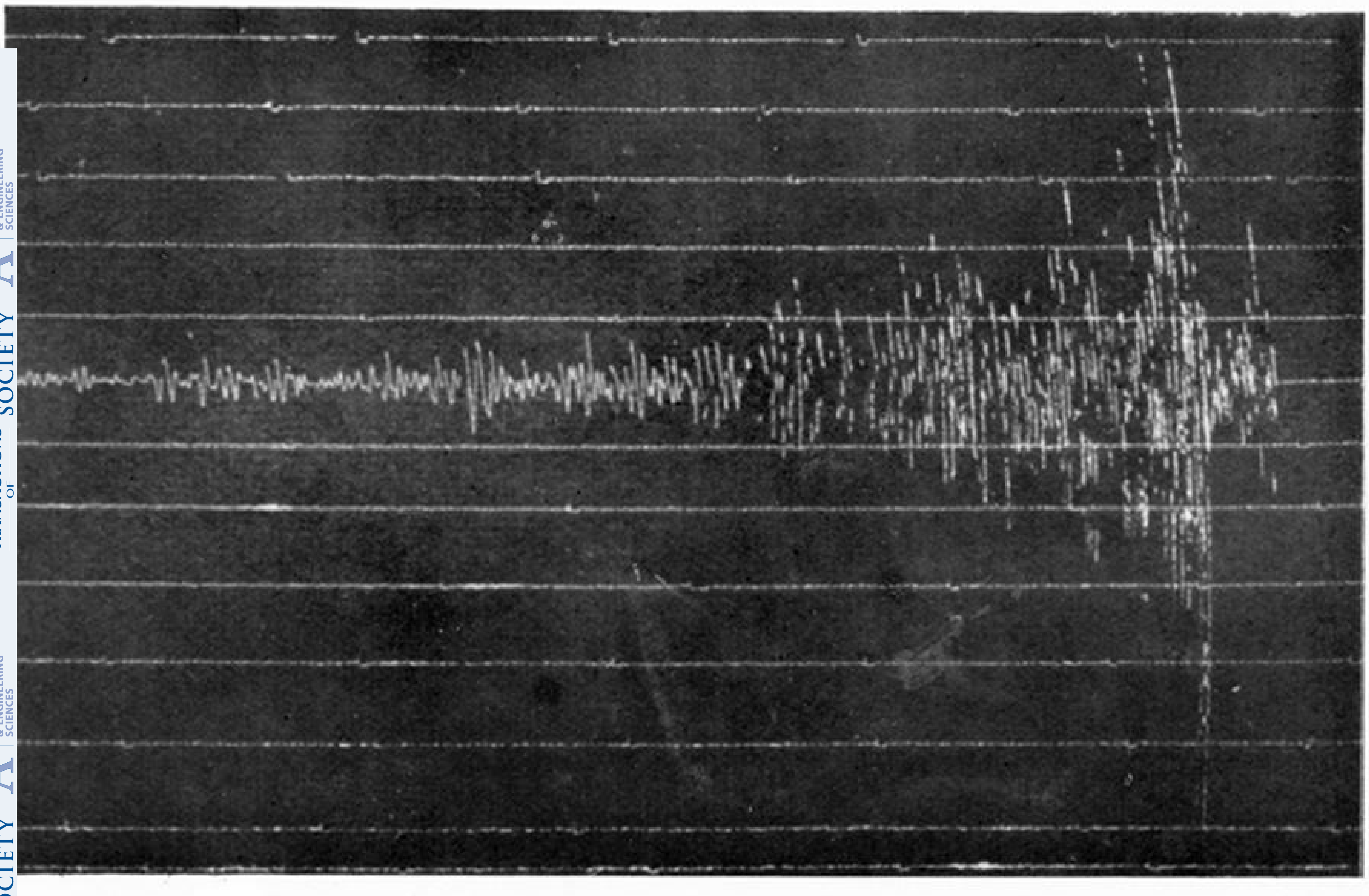
D 6



P–S, 11·4 secs.

D 8





P–S, 16·4 secs.

The interval between time marks on the records is one minute.

FIG. 14

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