2. *THE DERBY EARTHQUAKES OF JULY 3RD, 1904.* By CHARLES DAVISON, Sc.D., F.G.S. (Read December 21st, 1904.)

[PLATE II—MAP.]

I. INTRODUCTION.

BETWEEN the Derby earthquakes of March 24th, 1903, and July 3rd, 1904, there exist several points of intimate resemblance. The isoseismal lines of the two shocks, when drawn on one map, are so closely related that they might be the isoseismals of a single earthquake; both earthquakes were twins; the two epicentres in 1904 were nearly or quite coincident with those in 1903; and both earthquakes were followed by an after-shock, originating for the most part in the interfocal region of the fault. The points in which they differ are of little consequence. The intensity of the shock of 1903 was greater than that of the shock of 1904; the impulses at the two foci were approximately of the same strength in 1903, and of unequal strength in 1904; they occurred at the same instant on the former occasion, while, on the latter, they were separated by a brief interval of time.

The principal shock of 1903 occurred on a weekday at 1.30 p.m., that of 1904 at 3.21 on a Sunday afternoon. Thus, although of less intensity, the recent earthquake was felt and heard over a much wider area than its predecessor. There was at the time practically no traffic in the streets, and many of the observers (especially of those at a great distance from the centre) were lying down—conditions that favoured the observation of the earthquake in places at which, on an ordinary occasion, it would have passed totally unperceived.¹

There were at least three earthquakes in the series of 1904, namely:—

- (a) July 3rd, 2.28 p.m.
- (b) July 3rd, 3.21 p.m. (Principal earthquake.)
- (c) July 3rd, 11.8 p.m.

In addition to these, disturbances resting on the authority of a single record were reported at the following times:—

July 3rd, 3.15 p.m.: Tissington.—Two persons, in one room, thought that they heard thunder.

¹ I have to offer my best thanks to the very numerous observers who have placed their accounts at my disposal; to the editors of many newspapers who have given a wide circulation to my requests for information; and not least to those who on this, as well as on the former, occasion have been so kind as to collect records from other observers. Mr. H. H. Arnold-Bemrose has again aided me materially in this way, as have also Sir John G. N. Alleyne, Bart.; Mr. W. Wells Bladen, honorary secretary of the North Staffordshire Field-Club; Mr. W. F. Blay, of Wallsall; Mr. J. E. Bolton, of Eckington; Mr. W. J. Butcher, headmaster of the Grammar-School, Ashbourne; Mr. J. Clark, of

July 3rd, 3.23 P.M.: Dalbury Lees.—A low distant rumbling, as of thunder.
July 3rd, 4.20 P.M.: Grindon.—A heavy rumbling, without any attendant shock.

July 4th, about 1.30 A.M.: Matlock Bath.—A slight shock.

July 4th, about 6 A.M.: Wirksworth.—A slight shock.

II. FORE-SHOCK.

a. July 3rd, 2.28 P.M.

Intensity, 3. Number of records, 5, from 5 places.

A slight quivering was felt at Ambergate, Cromford, Matlock Bath, Mayfield, and Wirksworth (see map, p. 16). At Ambergate, a noise like a loud peal of thunder accompanied the tremor. Mayfield is about a mile south-west of Ashbourne. The other four places, however, are close to the north-eastern or Wirksworth epicentre of the principal earthquake, and the shock probably originated in the corresponding focus.

III. THE PRINCIPAL EARTHQUAKE. (Pl. II.)

b. July 3rd, 3.21 P.M.

Intensity, 7; centre of isoseismal 7, lat. $53^{\circ} 0' 4''$ N., long. $1^{\circ} 41' 6''$ W. Number of records, 1467, from 653 places, and 46 negative records from 44 places.

Time of Occurrence.

Excluding approximate estimates, the total number of records of the time is 737. Of these, 113 are regarded by their observers as accurate to the nearest minute. The average of all the latter is $3^h 21\frac{1}{4}^m$ P.M., and as the averages of the different zones included between successive pairs of isoseismals do not differ from this by more than a minute, it is probable that the time of occurrence at the epicentre was very nearly 3.21 P.M.

Isoseismal Lines and Disturbed Area.

The five continuous curves on the map of the earthquake (Pl. II) are isoseismal lines of intensities 7 to 3, the broken-and-dotted lines referring to the earthquake of March 24th, 1903.

Waterhouses, near Ashbourne; Mr. T. Gledhill, of Dronfield; Mr. C. W. Groves, of Risley; Mr. S. E. Howse, of Ambergate; Mr. A. V. Jones, of Church Broughton; Mr. T. W. Learoyd, of Rostherne, near Knutsford; the Rev. C. Price, of Denstone College; Mr. S. Steele, of Chesterfield; Mr. P. K. Tollit, headmaster of the Grammar-School, Derby; Miss A. C. Tute, headmistress of the High School for Girls, Derby; and Mr. W. M. Wilson, headmaster of the Higher Grade School, Hanley. By kindly writing on my behalf to the local press, Mr. Arnold-Bemrose has also prompted the communication of many valuable records. The expenses of the investigation were defrayed from a grant received from the Government Research-Fund.

The isoseismal 7 is approximately circular in form, $7\frac{1}{2}$ miles in diameter, and 41 square miles in area. Its centre lies about $1\frac{1}{2}$ miles east of Ashbourne in lat. $53^{\circ} 0' 4''$ N., long. $1^{\circ} 41' 6''$ W. The next isoseismal, of intensity 6, is roughly an ellipse, 37 miles long, 27 miles wide, and 804 square miles in area; the direction of its longer axis is N. 31° E. and S. 31° W., or very nearly parallel to the axis of the isoseismal 7 of the earthquake of 1903. The distance between the isoseismals 7 and 6 is 12 miles on the north-west side and 8 miles on the south-east. The most important feature in the two curves is, however, their excentricity: the distance between the centres of the two curves in the direction of the longer axis being about 2 miles. In the neighbourhood of Matlock Bath, there is another maximum of intensity 7 or nearly 7. The observations are insufficient to draw a second isoseismal in that district; but it is clear that, if the isoseismal corresponding to an intensity between 7 and 6 could be drawn, it would consist of two detached portions, one concentric with the isoseismal 7, the other not far from Wirksworth and Matlock Bath, their centres being separated by a distance of 6 or 7 miles. Thus, the two epicentres of 1904 are approximately coincident with those of the previous year.

The isoseismal 5 is the last which retains any trace of an elongated form. It is 72 miles long, 65 miles wide, and contains 3600 square miles; its distance from the isoseismal 6 is 21 miles on the north-west and 17 miles on the south-east side. The next two isoseismals are very nearly circles, the isoseismal 4 being 114 miles long from north-east to south-west, 113 miles wide, and about 10,120 square miles in area; the isoseismal 3, which forms the boundary of the disturbed area, is 181 miles long from north-east to south-west, 179 miles wide, and about 25,000 square miles in area. Observations were also made at a few places outside the latter isoseismal, at Aisgill, Appleby, Beckfoot, and Mallerstang in Westmorland; at Bridlington, on the east coast of Yorkshire; and at Long Whittenham, near Abingdon, in Berkshire.

Comparing the dimensions just given with those for the earthquake of 1903, we see that the isoseismals 7 to 4 of that earthquake are all larger than those for the earthquake of 1904; in 1903, a few buildings sustained slight injury over an area of 112 square miles, while, in 1904, there was practically no damage to property. On the other hand, the earthquake of 1904, owing to its occurrence on a Sunday afternoon, could be traced to a much greater distance, its disturbed area being about double of that of the earthquake of 1903.

Nature of the Shock.

In 1903, the twin-character of the earthquake was clearly defined; it was recognized by two out of every three observers, and was perceptible close to the boundary of the disturbed area. In 1904, only one out of five observers recorded the existence of two parts or

two maxima, and this was no doubt due to the incomplete separation of the two parts, an intermediate tremor being observed within the central area. Thus, at Ashbourne ($1\frac{1}{2}$ miles from the centre of the isoseismal 7), the shock consisted of a single series of vibrations, which increased in intensity to a maximum, and then died away; at Sudbury (about 9 miles to the south), there were two such maxima connected by weaker tremulous motion; at Birmingham (37 miles distant), two series of vibrations were felt, the first being distinctly stronger, the second series a mere shudder. The intermediate tremor was perceptible as far as Farnsfield near Southwell (27 miles from the centre); while the twin-shock was felt to the north at Bradford (5·4 miles), to the west at Ellesmere (50 miles), to the south at Stourport (5·2 miles), and to the east at Hough near Grantham (4·4 miles), or over an area of roughly 8000 square miles in extent.

This area is, however, traversed by a band within which the two parts of the shock were superposed. It is difficult to trace the boundaries of this band with accuracy, owing to the continuity of the shock within the central district; but the course of its median line probably does not differ much from that indicated by the broken-and-dotted line on the map (Pl. II), especially towards the south-east of the epicentre. This band differs in two respects from that traced for the earthquake of 1903. In that case, the band was rectilinear and about 5 miles in width; in the earthquake of 1904, it was hyperbolic in form, the concavity of the curve facing the south or south-west, and the width of the band is greater towards its extremities, being 15 or 16 miles at a distance of 30 miles from the centre. It will be noticed that the median line passes a short distance to the north-east of the centre of the isoseismal 7.

It is obvious from the distance to which the twin-shock was perceptible that there was some, although not much, difference between the intensities of the two parts. This conclusion is also borne out by the observations on the relative intensity of the two series or maxima. To the south-west of the hyperbolic band, 49 observers regarded the first part as the stronger, 9 the second, while 2 thought them roughly equal in intensity; to the north-east of the hyperbolic band, the corresponding figures are 20, 10, and 1. On the south-west side, however, 3 observers, and on the north-east side 8 observers, were doubtful as to the order of intensity. We may, I think, conclude from these figures that, while the first part was generally the stronger all over the disturbed area, the inequality was less on the north-east, than on the south-west, side of the hyperbolic band.

Outside the hyperbolic band, the length of the interval between the two parts varied from 1 to 4 seconds. The average of 75 estimates is 2·1 seconds, and the average is practically uniform throughout the disturbed area, being 2·2 seconds within the isoseismal 6, 2·0 seconds between the isoseismals 6 and 5, and 2·1 seconds outside the latter isoseismal.

Origin of the Double Shock.

There can be no doubt, from these observations, that the two parts of the shock originated in two foci lying along a line directed approximately from N. 31° E. to S. 31° W. A slight movement, however, took place in the intermediate region, sufficient to cause the tremulous motion felt between the two principal parts of the shock. If the impulses had taken place simultaneously, the two series would, as in 1903, have been superposed along a rectilinear band. As it is, the curvature of the hyperbolic band towards the south-western focus shows that the vibrations from the north-eastern focus travelled farther than those from the south-western focus before the two series coalesced. In other words, although the two impulses were nearly simultaneous, the north-eastern focus was in action a short time, perhaps a second or less, before the other.

In the present case, the positions of the two epicentres can be determined more accurately than in the earthquake of 1903. The south-western epicentre must coincide very nearly with the centre of the isoseismal 7, that is, it must be about $1\frac{1}{2}$ miles east of Ashbourne. The north-eastern epicentre probably lies near Wirksworth or Matlock Bath, and about 6 or 7 miles from the other.

Corroborative evidence of these determinations is afforded by the observations on the apparent direction of the shock. The sense of direction is more appreciable in houses in which the principal walls are at right angles to the direction of the epicentre; and it was found, in the case of the Hereford earthquake of 1896, that the average of a large number of observed directions, rough though they may be, points very nearly to the epicentre. For the recent Derby earthquake, it is possible to determine such average directions for two districts, one around Derby and the other around Nottingham, these two towns lying close to, but on opposite sides of, the hyperbolic band. In the Derby district, the mean direction is from W. 37° N., or exactly in a line from the centre of the isoseismal 7; in the Nottingham district, the mean direction is from W. 39° N., and, produced backwards, this line passes through a point 3 miles west of Wirksworth.

Lastly, the existence of the isoseismal 7 around the south-western epicentre and the practical absence of such a curve from the north-eastern epicentre lead to the conclusion that the impulse at the south-western focus was stronger, though not much stronger, than the impulse at the north-eastern focus. Consequently, on the south-west side of the hyperbolic band, the first part of the shock was the stronger; on the north-east side, the first part was as a rule the stronger, owing to the proximity of the north-eastern focus from which the first vibrations arrived.

Seismographic Records.

The seismographic records of the earthquake are of little interest, and do not add to our knowledge of its nature. Mr. W. E. Plummer,

director of the Liverpool Observatory at Bidston, near Birkenhead, informs me that, although the shock was felt by many persons there, the trace of the Milne seismograph shows but the slightest disturbance at 3^h 18·8^m P.M. In Birmingham, there was apparently no movement of the Omori horizontal pendulum, and only a minute displacement of the pointer of the Ewing duplex pendulum. The absence of a clearer record is probably due to the comparative weakness of the original disturbance, to the irresponsiveness of long-period horizontal pendulums to rapid vibrations, and, in the case of Birmingham, to the fact that the direction of the epicentre lies very nearly in the plane of the pendulum.

Isacoustic Lines and Sound-Area.

In drawing the isacoustic lines for the earthquake of 1903, the whole area was divided into squares by north-to-south and east-to-west lines 10 miles apart. I have made use of the same squares for the recent shock, but have calculated the percentage of audibility corresponding to the corners of these squares, making use of the records within the four contiguous squares. In this way a larger number of observations is at our disposal, the only effect of such a treatment being to smooth away local inequalities in the resulting curves. Notwithstanding this advantage, only one isacoustic line, corresponding to a percentage of 80, can be satisfactorily drawn. This is represented by the irregular dotted line on the map (Pl. II). Its peculiar form, especially the branches to the west and south-east, is evident at once. In the former direction, the number of records is too small to complete the curve, and its course may not be quite accurately laid down, but the branch evidently extends some distance farther towards the west. For the south-eastern branch, the observations are more numerous, and it will be noticed that it lies almost exactly along the course of the median line of the hyperbolic band. The explanation of this peculiarity, of course, is that the sound-waves from the two foci coalesced along the hyperbolic band, and were therefore audible to a larger number of observers. From the study of the sound-phenomena, we are therefore again led to the conclusion that the north-eastern focus was in action slightly before the other. With regard to the less-pronounced expansion of the curve towards the north, I can offer no satisfactory explanation.

With a few isolated exceptions, the sound was heard within the area bounded by the outer dotted line in Pl. II, a line which in no place deviates more than $4\frac{1}{2}$ miles from the isoseismal 4, overlapping that curve towards the east, south, and west, but not extending quite so far towards the north. Its dimensions are 121 miles from north-west to south-east, and 113 miles from north-east to south-west, and its area covers about 10,700 square miles. The exceptional records come from Branston Green (13 miles to the north of the boundary), Lytham (21 miles to the north-west)

Clunbury (6 miles to the south-west), and Wormleighton, Wroxton, and Brockworth (respectively 4, 11, and 27 miles to the south).

Though the sound-area is greater than in 1903, owing probably to the conditions at the time of occurrence, the percentage of audibility is somewhat less. Within the isoseismal 7, 94 per cent. of the observers heard the earthquake-sound; in the zone between the isoseismals 7 and 6, the percentage of audibility was 93; between the isoseismals 6 and 5, 79; between the isoseismals 5 and 4, 56; and outside the isoseismal 4, 38. The want of parallelism between the isacoustic line of percentage 80 and the boundary of the sound-area is probably due to the rapid decline in audibility as the latter curve is approached.

Nature of the Sound.

The total number of descriptions of the earthquake-sound is 812. In 45 per cent. of these, the sound is compared to passing traction-engines, motor-cars, etc., in 26 per cent. to thunder, in 15 to wind, in 5 to loads of stones falling, in 4 to the fall of a heavy body, in 2 to explosions, and in 2 per cent. to miscellaneous sounds.

The variation in the nature of the sound with the distance is shown in the following table (I), in which the figures are percentages of comparison to the different types for each of the districts mentioned:—

TABLE I.	Passing vehicles.	Thunder.	Wind.	Loads of stones falling.	Fall of a heavy body.	Explosions.	Miscellaneous.
Within isoseismal 7	39	41	0	9	2	9	0
Between isos. 7 and 6 ...	52	28	9	8	2	1	0
" " 6 " 5 ...	44	24	19	3	5	3	2
" " 5 " 4 ...	35	24	25	4	4	2	6
Outside isoseismal 4	40	33	27	0	0	0	0

The most noticeable variation is the increase with distance in the proportion of comparisons to the smooth and monotonous type of wind.

Time-Relations of the Sound and Shock.

In the following table (II, p. 15), the letters *p*, *c*, and *f* indicate the number of records per cent. in which the beginning or end of the sound preceded, coincided with, or followed, the corresponding epoch of the shock; the letters *g*, *e*, and *l* show the number of records per cent. in which the duration of the sound was greater than,

equal to, or less than, that of the shock. The last line of the table gives the percentages for the Derby earthquake of 1903:—

TABLE II.	BEGINNING.			END.			RELATIVE DURATION.		
	<i>p</i>	<i>c</i>	<i>f</i>	<i>p</i>	<i>c</i>	<i>f</i>	<i>g</i>	<i>e</i>	<i>l</i>
Within isoseismal 7	70	30	0	7	47	47	71	29	0
Between isoseismals 7 and 6	62	32	5	24	52	24	51	39	10
" " 6 " 5	68	24	8	12	53	35	73	25	2
" " 5 " 4	70	24	6	28	43	28	70	9	22
Whole sound-area	65	29	6	18	51	31	62	31	7
" " of the earthquake of 1903	57	37	7	21	55	24	46	46	9

For the epoch of maximum intensity, the number of records is only 37. The epoch when the sound was loudest preceded that when the shock was strongest in 30 per cent. of the records, coincided with it in 62, and followed it in 8 per cent.

The chief result of the foregoing table is the rough approach to uniformity for the different zones, whatever their distance from the epicentre. If the sound-waves travelled more rapidly than those of larger amplitude, we should expect to find an increase with distance in the observations of the sound before the shock, and a decrease in those of the sound after the shock. Except in the central area, in which both fore-sound and after-sound would naturally be more sensible, there is no distinct trace of such variation.

IV. AFTER-SHOCK.

c. July 3rd, 11.8 P.M.

Intensity, 4; centre of isoseismal 4, in lat. $53^{\circ} 28'$ N., long. $1^{\circ} 39.5'$ W. Number of records, 76, from 42 places, and 2 negative records from 2 places (map, p. 16).

In the map of this after-shock (p. 16), the continuous lines represent the isoseismals 4 and 3, the dotted lines are the corresponding isoseismals for the after-shock of May 3rd, 1903; the broken-and-dotted line is the isoseismal 7 of the principal earthquake of 1904.

The isoseismal 4 is 16 miles long, 10 miles wide, and contains 125 square miles. Its centre is about half-a-mile south-west of Hognaston, and the direction of its longer axis about N. 27° E. and S. 27° W. The course of the isoseismal 3 is somewhat doubtful towards the north and south, but the error in either case is probably less than a mile. As drawn, it is 27 miles long, 20 miles wide,

and contains 425 square miles. The distance between the two isoseismals is 6 miles on the north-west, and $4\frac{1}{2}$ miles on the south-east, side. The shock and sound were also observed, though very faintly, at Derby, $1\frac{1}{2}$ miles south-east of the isoseismal 3, and at Leek, $4\frac{1}{2}$ miles west of the same curve.

Map illustrating the area affected by the after-shock of July 3rd, 1904.

The shock is uniformly described as a continuous series of rapid vibrations, the average of four estimates of its duration being $3\frac{1}{2}$ seconds. The sound was heard by 96 per cent. of the observers, and was compared to passing vehicles in 28 per cent. of the records, to thunder in 39 per cent., to wind in 11, to the fall of a load of stones in 6, and to explosions in 17 per cent. The beginning of the sound either preceded or coincided with that of the shock; the end of the sound generally coincided with that of the shock.

V. ORIGIN OF THE EARTHQUAKES.

The elements of the originating fault, as determined by the seismic evidence for both the principal earthquake and the after-shock, are as follows :—(1) the mean direction of the fault is from N. 31° E. to S. 31° W. ; (2) its hade is to the north-west ; and (3) the fault must pass through a point a short distance to the south-east of the centre of the isoseismal 7, that is, it must pass through or near the village of Hognaston. Comparing these elements with those obtained for the fault in action in 1903, we see that they are almost identical, the only difference being the slight one of 2 degrees in the mean direction of the fault. We may, therefore, conclude with some probability that the two earthquakes originated in slips along the same fault; and the probability seems strengthened when we consider that the two epicentres in both earthquakes were practically coincident.

In 1903 there was no distinct preparation for the earthquake of March 24th; the impulses occurred simultaneously within the two foci and were very nearly equal in strength, and there was no sensible movement in the interfocal region of the fault. In less than 4 hours two small slips took place in unknown parts of the fault; and 40 days later, on May 3rd, the increased stresses at both ends of the interfocal region resulted in a slip chiefly within that region, partly perhaps within the nearer lateral margins of the foci, but closer to the surface than the two principal slips of March 24th.

In 1904, on the other hand, there was a preliminary slip within the north-eastern or Wirksworth focus, followed in less than an hour by the principal slips in both foci, that within the south-western or Ashbourne focus being the more pronounced and succeeding the other by about a second or even less. In this case the foci were not completely detached, for throughout the interfocal region there was a slight displacement, comparable in magnitude with that which occurred in the marginal regions of the principal foci. In other words, the nearer margins of these foci coalesced. About 8 hours later the increased stresses resulting from these movements precipitated an interfocal slip, at about the same depth as the previous slips in the principal foci. With this, the series of movements seems to have terminated, unless there were two small creeps a few hours later within the Wirksworth focus.

EXPLANATION OF PLATE II.

Map of the area affected by the principal Derby earthquake of July 3rd, 1904, on the scale of 15 miles to the inch.

[For the Discussion, see p. 33.]

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MAP illustrating
the AREA affected by the PRINCIPAL
DERBY EARTHQUAKE
of JULY 3rd, 1904.
By CHARLES DAVISON, Sc.D., F.G.S..