One Upper Silurian species (Fig. 2), *B. thysanopeltis*, Barr.,¹ has as many as forty-five marginal spines on its caudal shield, while another detached pygidium shows thirty-three spines upon its border² (Fig. 3). *B. (Thysanopeltis) speciosus*, Corda, from the Lower Middle Devonian, has forty marginal spines around its caudal shield³ (Fig. 4), while another Devonian form referred to by Barrande⁴ has about twenty-two spines.⁵

We may, I think, safely conclude that Mr. Townshend Hall's Gerolstein specimen is quite distinct from any other Devonian form. It may be characterized as having seven coalesced segments in its caudal shield, indicated by seven marginal spines, marking the lateral termination of the pleuræ, and by a single *non*-bifurcate stout median lobe, being a prolongation of the axis of the caudal shield, and terminated by a similar median spine upon its margin. The decorticated portion of the margin of the shield shows that the underside was etched by numerous fine parallel wavy lines, extending over even the lower surface of the marginal spines.

I propose to designate this Gerolstein form as *B. Halli*, after my late friend Townshend M. Hall, who did so much good work in the Devonian rocks of North Devon.

IX.—THE CHARACTERISTICS OF BRITISH EARTHQUAKES: A SUMMARY OF TWENTY-ONE YEARS' WORK.

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

FOR a detailed study of the earthquakes of any district, an interval of twenty-one years is too brief. Long-period variations of frequency cannot be established. We can form no satisfactory conception of the distribution of seismic energy in space, for some foci may lie inactive for a much longer time, while others may continue in operation without apparent change. But, to ascertain the characteristic features of the earthquakes, to investigate their relations with those which precede and follow them, or to trace their connexion with the structure of the central districts, such an interval is possibly of sufficient length. In any case, the defects resulting from its brevity may be partly compensated by uniformity in treatment and in the methods of investigation.

¹ J. Barrande, *Système Silurien du Centre de la Bohême*, pt. i, vol. i, 1852, Texte Crustacés: Trilobites, p. 843, pl. xlvii, fig. 6.

² Op. cit., pl. xlvii, figs. 11, 12.

³ Kayser's *Text-book of Comparative Geology* (translated and edited by Philip Lake), p. 121, fig. 5, 1893; and Gürich, *Leitfossilien*, Taf. xlvii, fig. 1.

⁴ See explanation to pl. xlvii, under fig. 12.

⁵ Barrande writes—" *Bronteus acanthopeltis* (Schnur) was recently discovered in the Eifel by Professor Schnur, of Trèves. It presents the nearest analogy with *B. thysanopeltis*. It is distinguished, however, by possessing less than half the number of spines around the pygidium. It only came to our knowledge by the kindness of Professor Schnur, who was so good as to send it to us at the moment when our text was going to press." [I cannot, I regret to say, find any figure of this species.]

The earthquakes of the last twenty-one years have been in no respect unusual. None has exhibited in its central area so destructive an intensity as the Colchester earthquake of 1884. Nor has any borne a train of after-shocks so numerous as that of the Comrie earthquake of 1839. Three earthquakes (those of Hereford in 1896, Inverness in 1901, and Swansea in 1906) were, however, strong enough to cause considerable damage to buildings; and, in the low-lying country on the south side of the Ochil Hills, there have been many slight shocks which in their nature and frequency approximate towards those which have made the name of Comrie famous.

Several of the more important seismic centres in this country have lain dormant or nearly so during these years. Rumbling noises, apparently underground, are said to have been heard in West Mersea Island, off the coast of Essex, and, if seismic, may possibly be connected with the centre which gave rise to the Colchester earthquake twenty-six years ago. The Comrie focus is represented by three slight shocks, and seems to have relapsed into that state of quiescence which may precede another outburst of energy. On the other hand, the important focus in the neighbourhood of Inverness has been unusually active, and other well-known foci have exhibited those signs of flickering vitality which from time to time interrupt the monotony of our geological existence.

Hardly any part of Great Britain has been entirely free from the transitory effects of earthquake shocks, the only districts left undisturbed being the greater part of Durham and Northumberland and some of the southern counties of Scotland.

FREQUENCY.

Taking into account only those earthquakes recorded by more than one observer, the total number which have occurred in Great Britain during the interval considered is 250, the greatest numbers in any single year being 25 in 1890, 23 in 1901 and 1906, and 20 in 1892, and the least numbers being 1 in 1897 and 1899, and 2 in 1895 and 1902. Of the total number, 50 (including two with submarine origins off the coasts of Cornwall) originated in England, 27 in Wales, and 173 in Scotland. Thus, on an average, one earthquake occurs in Great Britain every month. Also, out of every 20 earthquakes, 4 occur in England, 2 in Wales, and 14 in Scotland; or, taking area into account, 2 occur in England, 7 in Wales, and 11 in Scotland.

INTENSITY AND DISTURBED AREA.

Of the 250 earthquakes, 3 were of intensity 8 of the Rossi-Forel scale, 9 of intensity 7, 7 of intensity 6, 29 of intensity 5, 64 of intensity 4, 127 of intensity 3 or about 3, while 11 were merely earth-sounds unaccompanied by any perceptible tremor. In Japan, 220 of the shocks would be described as weak, 16 as strong, and 3 as violent; in Italy, 127 would be considered slight, 64 moderate, 36 strong, and 12 very strong.

The connexion between the intensity of the shocks and the areas disturbed by them is shown in the following table:—

TABLE I.

Intensity.	Disturbed Area in Square Miles.		
	Maximum.	Minimum.	Average.
8	98000	33000	65900
7	63600	1000	24500
6	3100	74	1200
5	3000	90	850
4	1130	28	260
3	219	18½	126

The intensity at the epicentre is not, however, proportional to the energy expended in producing an earthquake, for it depends to a great extent on the depth of the focus and the nature of the surface rocks. A more satisfactory though still a rough test is the area included within a given isoseismal, say that of intensity 4.¹ If an earthquake be regarded as *strong* when this area exceeds 5000 square miles, as *moderate* when it lies between 1000 and 5000 square miles, and as *slight* when it is less than 1000 square miles, then Great Britain has been visited during the last twenty-one years by 9 strong, 7 moderate, and 223 slight earthquakes, and 11 earth-sounds.²

PERIODICITY.

The monthly distribution of earthquakes is given in the next Table (II), the upper figure denoting the number of earthquakes during the first 14 days in February and the first 15 days in each of the other months, the lower figure the number observed during the remainder of each month.

TABLE II.

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
7	2	7	10	8	2	17	3	2	9	8	6
17	6	7	4	9	17	6	17	28	19	11	28

Applying the method of overlapping means³ to determine the annual and semi-annual periods, it appears that there is a well-marked annual period with its maximum in October, the amplitude being

¹ The disturbed area is an unsatisfactory test, for the Pembroke earthquake of 1893 was felt over a larger area than the stronger shock of 1892, and the Derby earthquake of 1904 than the stronger earthquake of 1903.

² The strong earthquakes are those of Pembroke in 1892 and 1893, Hereford in 1896, Inverness in 1901, Derby in 1903 and 1904, Carnarvon in 1903, Doncaster in 1905, and Swansea in 1906. The moderate earthquakes are those of Bolton in 1889, Inverness in 1890, Leicester in 1893, Carlisle in 1901, Strontian in 1902, Derby in 1906, and Oban in 1907.

³ Phil. Trans., 1893 A, pp. 1108-15; Boll. della Soc. Sismol. Ital., vol. iv, 1898, pp. 89-100.

·37 of the average monthly number. The semi-annual period is less pronounced, and its reality is doubtful owing to the smallness of the amplitude, which is only ·14. The analysis gives the maximum epochs in the middle of May and November.

The next Table (III) illustrates the hourly distribution of the earthquakes, those which are reported as occurring at the exact hours being divided equally between the hours before and after.

TABLE III.

	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12
a.m. .	9	17	6·5	10	16	9	9·5	10	8·5	9·5	10	6
p.m. .	4	10	5	7	16	9	9	6	5	11	12	9

As the shocks were not recorded instrumentally, it is useless applying the method of overlapping means to these figures. The variations in frequency are no doubt chiefly due to more favourable conditions existing at certain times of the day, as, for example, the early hours of the night (9 to 11) and the hour 1 to 2 a.m., when many persons lie awake after their first sleep. The increase of apparent frequency in these hours is manifest in every earthquake catalogue, but a feature which seems to be peculiar to British earthquakes is the large number felt from 4 to 5 p.m. Of the sixteen earthquakes recorded during this hour, seven occurred on Sunday, while two others were strong shocks that could not have passed unnoticed at any time of the day. It is, therefore, probable that the number of slight shocks recorded in Great Britain would be almost doubled if all the hours of the day were as restful as those devoted to the modern institutions of the Sunday afternoon siesta and the 5 o'clock tea.

NATURE OF THE SHOCK.

As a general rule, in British earthquakes the shock consists of a single series of vibrations, which increase rapidly in strength, until one or several of greater prominence are felt, after which they fade as rapidly away. The average duration of the shock in such cases is about four seconds, though, as in the Carnarvon earthquake of 1903, it may be as much as 6·7 seconds. In very slight earthquakes there are no prominent vibrations, and only a weak tremor is perceived; in slight earthquakes the shock often begins with a single prominent vibration, like the thud of a falling body, followed by a brief tremor as such a fall would produce in a building. In these earthquakes the average duration of the shock seldom exceeds two seconds and is often less.

In a few earthquakes the shock consists of two parts, in each of which the vibrations increase to a maximum and then die away. The two series generally differ in intensity and duration, and occasionally in the period of their vibrations. As a rule, the interval between the two parts is one of absolute rest and quiet, but occasionally it is occupied by a weak tremor and sound which are

observed only near the epicentre, so that, at a distance from that region, the shock consists of two entirely detached parts. The average duration of the interval of rest is 2·7 seconds, and that of the whole shock about six or eight seconds, rising, as in the Hereford earthquake of 1896, to 9·3 seconds. It is now known¹ that, in these cases, the double shock is caused by impulses in two distinct foci, the impulses being either simultaneous or separated by an interval which is often less than the time taken by the earth-waves to travel from one focus to the other. Of the 250 earthquakes, at least eleven (or about 4 per cent.) belong to this class of twin earthquakes.

SOUND-PHENOMENA.

The sound which accompanies an earthquake is a deep rumbling sound, so low that it is inaudible to some persons, while to others in the same place it appears louder than any thunder. That the inaudibility is not due to inattention is clear from the fact that, in the Inverness earthquake of 1901 (which occurred at 1.24 a.m.), 86 per cent. of the observers who were awake, and 84 per cent. of those who were asleep, heard the sound which preceded the shock. For the Doncaster earthquake of 1905 (which occurred at 1.37 a.m.) the corresponding figures are 93 and 91 per cent.

Of the 250 earthquakes, 197 (or 79 per cent.) were certainly accompanied by sound. In 4 cases, the observers state that they heard no sound; in 49 cases, no reference is made to the sound-phenomena. Of these 53 earthquakes, 28 occurred in the Ochil district, 10 in Glen Garry, 11 were after-shocks of strong earthquakes, and 4 were slight earthquakes in various places. But all, without exception, were feeble tremors, the number of observers was small, and there can be little doubt that, with a larger number, there would have been some who would have heard and recorded the sound. It is probable, therefore, that all British earthquakes are attended by audible vibrations.

In strong earthquakes the sound was heard on an average by 83 per cent. of the observers, in moderate earthquakes by 93 per cent., and in slight earthquakes by 97 per cent. This difference is partly due to the fact that, in slight earthquakes, the sound is generally a much more prominent feature than the shock, and partly to the variable size of the sound-area. In slight earthquakes, the sound-area either coincides with or overlaps the disturbed area; in moderate earthquakes, the two areas are approximately coincident; in strong earthquakes, the sound-area falls short of the boundary of the disturbed area, the sound-area varying from 43 per cent. of the disturbed area in the Derby earthquake of 1904 to 82 per cent. in the Inverness earthquake of 1901. On an average, the sound-area is 64 per cent., or roughly two-thirds, of the disturbed area.

In moderate and slight earthquakes, the percentage of audibility is practically uniform throughout the area affected. In strong earthquakes, with a large disturbed area, the decline in audibility as the

¹ Quart. Journ. Geol. Soc., vol. lxi, 1905, pp. 18-33.

sound-waves recede from the centre is distinctly marked. Within the central isoseismal, 97 per cent. of the observers on an average hear the sound, and in the successive zones bounded by the isoseismals, the average percentages of audibility are 94, 88, 69, and 60 respectively. Close to the boundary of the sound-area, there is a rapid decline to zero.

The sound may be classified under one of the following types: (1) Wagons, trains, traction-engines, etc., passing, (2) thunder, (3) wind or a chimney on fire, (4) loads of stones falling, (5) the fall of a heavy body, (6) explosions, and (7) miscellaneous sounds, such as the trampling of many animals, the roar of a waterfall, etc. The following Table (IV) shows the average frequency of reference (in percentages of the total number) to these different types for the three classes of British earthquakes. In the last two lines of the table are given separate figures for two divisions of slight earthquakes, the first division having a long focus and the second division a short focus.

TABLE IV.

Earthquakes.	Type.						
	1	2	3	4	5	6	7
Strong	46	24	10	5	3	7	5
Moderate	49	26	4	5	5	8	3
Slight	33	29	5	7	9	14	3
„ (long focus) . .	40	37	4	1	4	10	4
„ (short focus) . .	29	26	6	9	11	16	3

Omitting the seventh type, the first three may be regarded as of long and the next three as of short duration. The percentage of reference to types of short duration is 16 for strong earthquakes, 19 for moderate earthquakes, 31 for slight earthquakes, or 16 for slight earthquakes with a long focus and 37 for those with a short focus. It will be noticed that the sounds attending strong and moderate earthquakes, and also slight earthquakes with a long focus, are approximately of the same character.

In the neighbourhood of the epicentre, the sound varies greatly in character and intensity. When the shock begins, the sound becomes deeper and more rumbling, and with the strongest vibrations deep booming explosive crashes are heard by those observers who possess a low limit of audibility. In the zone outside the central isoseismal the crashes are less frequently heard, but still the sound changes perceptibly while the shock is felt, becoming rough and grating; while, near the boundary of the sound-area, it is a low monotonous moan like the boom of very distant thunder. Table V shows the variation in type in strong earthquakes, beginning with the central zone A, and continuing with the zones B, C, D, E, bounded by successive pairs of isoseismals.

TABLE V.

Zone.	Type.						
	1	2	3	4	5	6	7
A	36	30	6	8	3	12	4
B	44	28	9	6	5	7	5
C	50	22	11	4	5	5	4
D	47	21	15	3	4	4	5
E	47	21	25	1	1	1	1

Thus, as the distance from the origin increases, there is a steady diminution in the references to types 2, 4, and 6, an increase in those to type 3, and on the whole an increase in those to type 1.¹ Omitting type 7, the percentage of references to the types of long duration (1 to 3) for successive zones are 76, 81, 86, 88, and 94, implying, not that the duration of the sound increases, but that the sound becomes smoother and more monotonous in the outer zones.

Occasionally, the sound is heard before the shock and becomes inaudible as soon as the first vibrations are felt. With a very few exceptions, however, the sound, when heard at all, accompanies the shock, though it is heard by many observers both before and after the shock. The time-relations of the principal epochs of the sound and shock are given in Table VI, in which the figures in the columns headed *p*, *c*, and *f* denote the number of records per cent. in which each epoch of the sound preceded, coincided with, or followed the corresponding epoch of the shock; those in the columns headed *g*, *e*, and *l* denote 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.

TABLE VI.

Earthquakes.	Beginning.			End.			Epoch of Max. Int.			Relative Duration.		
	<i>p</i>	<i>c</i>	<i>f</i>	<i>p</i>	<i>c</i>	<i>f</i>	<i>p</i>	<i>c</i>	<i>f</i>	<i>g</i>	<i>e</i>	<i>l</i>
Strong . .	66	25	9	15	40	45	22	68	10	68	27	5
Moderate . .	66	29	5	12	43	45	24	73	3	75	23	2
Slight . .	59	34	7	14	47	40	33	67	...	58	41	1

This table shows that there is a close resemblance, as regards time-relations, between all three classes of earthquakes. Roughly speaking, two out of every three observers who hear the sound at all hear the fore-sound, two out of every five hear the after-sound, while to two out of every three the sound is loudest at the instant when the shock is strongest.

¹ The slight decrease in the two outer zones is probably due to the comparative uniformity in the intensity of the sound at great distances.

The next Table (VII) shows how slightly the time-relations of the sound and shock vary throughout the sound-areas of strong earthquakes.

TABLE VII.

Zone.	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>
A	67	30	3	19	42	38	70	28	2
B	69	24	7	15	42	44	69	24	7
C	70	20	10	15	44	41	66	27	7
D	63	25	12	21	44	36	54	38	8

The precedence of the shock by the sound is generally attributed to a greater velocity of the sound. If this were the case, however, the sound, with increasing distance, would be more generally heard before the shock and less frequently after it. There is no evidence whatever of such a displacement of the sound in the above Table. The only tendency distinctly noticeable is towards equality in the relative duration, and this might be expected from the gradual quenching of the weaker vibrations which constitute the fore-sound and after-sound.

MINOR SHOCKS.

The series of slight shocks which occur in Great Britain belong to two classes, one including those which have been confined to Glen Garry and the Ochil district, the other those which precede and follow the stronger earthquakes.

The Glen Garry series lasted for about ten years, from 1889 to 1899. In this interval 41 slight shocks were recorded, the majority occurring during the three years 1890–2, when the numbers felt were 11, 18, and 6 respectively. The Ochil series began in the year 1900, and is still (1910) continuing with unabated frequency. Up to the end of 1909, the total number recorded is 83, 4 having occurred in 1900, 1 in 1903, 10 in 1905, 19 in 1906, 13 in 1907, 17 in 1908, and 18 in 1909. They vary considerably in intensity. Two, namely, those of September 21, 1905, and October 20, 1908, were strong within the epicentral district, and each disturbed an area of about a thousand square miles. But they should be regarded as stronger shocks than usual, rather than as the parents of trains of after-shocks, for the slight shocks which followed were not more frequent immediately after them than at other times.

True accessory shocks are almost confined to the strong earthquakes which disturb areas of more than 5000 square miles. The total number of such shocks is 71, all but five of which attended the strong earthquakes and the Inverness earthquake of 1890, and of the majority 15 were fore-shocks and 51 after-shocks. It is worthy of notice that, as regards after-shocks, there is a marked difference between simple and twin earthquakes. The three simple earthquakes of Inverness in

1890 and 1901 and Carnarvon in 1903 were followed by 33 after-shocks, and the seven strong twin earthquakes by 18 after-shocks.

DISTRIBUTION IN SPACE.

The total number of earthquakes which it is possible to associate with known lines of fault or folding is 199.¹ Of the 199 earthquakes, 153 were probably connected with faults of the Caledonian system, 23 with Charnian, 10 with Malvernian, and 13 with Armorican faults. In Scotland, with the exception of the Loch Broom earthquake of 1892, which was connected with a Charnian fault, the remaining 129 shocks were due to movements along Caledonian faults. In England 15 earthquakes were connected with Caledonian faults, 22 with Charnian, 6 with Malvernian, and 5 with Armorican faults. In north-west and central Wales, the earthquakes were connected with Caledonian faults, in the south of Wales with Armorican faults. Of the nine strong earthquakes, the Inverness earthquake of 1901, the Derby earthquakes of 1903 and 1904, the Carnarvon earthquake of 1903, and the Doncaster earthquake of 1905 were connected with Caledonian faults, the Hereford earthquake of 1896 with a Charnian fault, and the Pembroke earthquakes of 1892 and 1893 and the Swansea earthquake of 1906 with Armorican faults. The last four earthquakes were the strongest felt in this country throughout the twenty-one years. Twin earthquakes are entirely confined to England and the south of Wales.

ORIGIN OF BRITISH EARTHQUAKES.

The study of British earthquakes has led to the association of a large number of them with known faults, especially in those in which there is reason to think that the foci were situated at a small depth. In other cases, the investigation of the earthquakes has thrown light on the structure of the epicentral districts at depths far beyond the reach of methods at the disposal of the field-geologist. For instance, the complicated structure of the English Lake District is superposed on one of a more simple character, the Carlisle earthquakes of 1901 having originated in a fault not less than 23 miles in length, and directed approximately N. 5° E. Similarly, in south Glamorgan, as shown by the Swansea earthquake of 1906, a fault at least 22½ miles long runs in a direction about E. 5° N. from west of Swansea to the neighbourhood of Llwynpia.

A rough approximation to the length of the seismic focus is given by the difference in length between the longer and shorter axes of the innermost isoseismal.² In estimating the average length of the focus for the different classes of British earthquakes, after-shocks are omitted, as in them the length of the focus is governed to some extent by that of the principal earthquake. The results are as follows:—

¹ The earthquakes omitted are the 41 shocks felt in Glen Garry from 1889 to 1899, 2 shocks near Tadcaster in 1890, 5 in Pembrokeshire in 1893, 3 in Annandale in 1894 and 1896, and 1 near Beddgelert in 1904.

² Gerland's *Beitrag zur Geophysik*, vol. ix, 1908, p. 224.

TABLE VIII.

Earthquakes.	Mean length of focus in miles.
Strong . .	12 $\frac{1}{4}$
Moderate . .	13
Slight, <i>a</i> . .	12
„ <i>b</i> . .	4 $\frac{1}{4}$

Slight earthquakes are obviously divisible into two sub-classes, the first in which the focus is 9 miles or more in length, the second in which the focus is 6 miles or less in length.¹ The above Table gives the reason why the sound should be of nearly the same character in strong, moderate, and the first division of slight earthquakes. Thus, the intensity of all but the slightest earthquakes depends, not on the magnitude of the focus, so much as on the amount of relative displacement along the surface of the fault.

British earthquakes, according to the nature of the shock, are divisible into two classes, simple and twin, and this classification corresponds to a difference in origin. Simple earthquakes are due to continuous slips, as a rule along strike faults; twin earthquakes are caused by rotation of the median limb of a crust-fold along a transverse fault, the two foci coinciding with the crest and trough of the fold, the interfocal region with the practically undisplaced portion of the median limb about which the rotation takes place. In this connexion, it is worthy of notice that the average distance between the epicentres of British twin earthquakes is 10 or 11 miles, which agrees closely with the average distance of 9 to 12 miles between the crests of the great crust-folds in France.

The average length of the focus in twin earthquakes is about 12 miles. Thus, the average length of focus in twin earthquakes and in other earthquakes, whether strong or moderate or, in certain cases, slight, is nearly the same, and is probably equal to, or it may be slightly more than, the average distance between the crests of the crust-folds. In other words, the magnitude of the crust-folds seems to determine the length of fault-slips along strike faults as well as along transverse faults.

NOTICES OF MEMOIRS.

I.—THE SIGNIFICANCE OF EARLY AND OF PLEISTOCENE GLACIATIONS.² By MARSDEN MANSON, Ph.D.

THE objects of this paper are to point out the significant differences between the preceding, accompanying, and succeeding phenomena of early glaciations and the corresponding phenomena of Pleistocene

¹ In determining the average for the second sub-class, a large number of very slight shocks were unavoidably omitted; their inclusion would, of course, lower the average considerably.

² Being an abstract of a paper read before the Eleventh Session of the Int. Geol. Congress, Stockholm, August, 1910.