# The origins and nature of microseisms in the frequency range 4 to 100 c/s

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[Plates 1 to 4]

Microseisms in the frequency band 4 to 100 c/s, commonly encountered in seismic prospecting, have been investigated in various parts of England, urban and rural. A diurnal variation in background level, indicating man-made sources, was found everywhere within 2 miles of a major road or community. The main sources were found to be traffic, heavy machinery, aircraft, wind and rain, with traffic prevailing. In rural areas at night-time a steady background of about $10^{-6}$ cm/s r.m.s. particle velocity was found, with occasional superimposed activity lasting 4 to 30 s. The latter has been shown mostly to be local and of geophysical origin, the precise nature of which is unknown. Various possible causes are discussed, both of this and of the minimum background.

## 1. INTRODUCTION AND ACKNOWLEDGEMENTS

In contrast to the considerable work which has been done on long-wave microseisms, of period 3 to 10 s (Lee 1932*a*, *b*; 1934; Whipple & Lee 1935; Ramirez 1940; Longuet-Higgins 1950; and others), little attention has been paid to those movements of the ground which lie in the frequency band 4 to 100 c/s, other than those generated by explosives. This is due partly, no doubt, to the widespread assumption that they are of man-made origin, or that they derive from meteorological causes such as wind, rain, etc. As will be shown, however, natural earth movements, of a type not hitherto discussed, provide a further source. In addition, the study of the nature of short-wave microseisms is of practical importance in that they form an undesirable background to seismic prospecting in just the same way as long-period microseisms interfere with earthquake recording. If the sources and the frequencies could be easily classified and predicted, it would, in principle, be possible to site the geophones, time the shots, and introduce electrical filters, in such a way that the background is reduced to the minimum; the greatest 'signal-to-noise' ratio thus being obtained, and the maximum sensitivity determined which could be usefully employed for seismographs and geophones.

This was recognized by Dr E. C. Bullard and Dr M. N. Hill and, at the Department of Geodesy and Geophysics, Cambridge, the latter started to examine the origin and nature of these short-wave microseisms. At the suggestion of Dr Bullard the author participated at an early stage, and continued the project when Dr Hill resumed other work. The programme consisted in recording the variations in level and the alteration in the spectral distribution of energy, of the microseismic background at a number of sites, rural and urban. By correlation of the

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variations in level with site and conditions it was hoped to find the important factors regulating the disturbances; by comparing the frequencies obtained with those characterizing certain common forms of man-made activity it was hoped to isolate some of the man-made sources of the disturbance. An account is given in a companion paper (Wilson 1953) of the separate study of the vibrations produced from traffic and heavy machinery, and of the spectral distribution of energy at one site.

The instruments were largely designed and built by Hill, and there follows a short description of these, and of his preliminary results. The author gratefully acknowledges this contribution. The work was carried out chiefly under the supervision of Dr R. I. B. Cooper, without whose guidance and active co-operation few results would have been achieved. Thanks are also due to Mr B. C. Browne for his interest and encouragement, and, finally, to Mr J. C. Swallow who joined in the work for a short time and built a very satisfactory frequency analyzer.

## 2. Instruments

The geophones used were of the electro-magnetic moving-coil type, whose natural frequency was 4 c/s. A damping resistance approximately equal to that of the coil gave the geophones a frequency response 'flat' from 8 c/s upwards. Three vertical and two horizontal recording geophones were constructed, the characteristics of all being as nearly as possible identical. Three channels were employed, allowing the simultaneous recording either of all three vertical geophones in separate places, or of the three components in one place. Amplifiers were used which provided, with the input transformer, a total possible gain of $3 \times 10^7$. Either the a.c., or rectified output, or both, was recorded, as occasion demanded. With the cameras used, more than 24 h continuous recording was possible. The geophones were calibrated absolutely in the laboratory on a shaking table; their final sensitivity, after damping, was found to be 0·16 V/cm sec.

The problem of calibration in the field was dealt with in the following manner, which is perhaps novel. A synchronous motor was fitted with an arm mounted on the spindle. When the arm is spun, the motor acts as a dynamo and runs through all frequencies, from 100 c/s downwards, until the arm comes to rest. A choke in series with the motor keeps the output constant at about 1 mV at all speeds. A suitable fraction of the output is tapped off and fed into the amplifier, thus serving as an absolute calibrator and also as a check on the frequency response of the system.

This device was also used if the geophones were suspected to be constrained in any way. When the arm is spun the output will pass through the natural frequency of the geophone just before stopping; the system will then resonate slightly if the geophone is free, causing an unmistakable upward flicker on the amplifier meter.

Much trouble was experienced in the early stages from mains interference. This is partly electro-magnetic and partly electrostatic (see Bullard, Gaskell, Harland & Kerr-Grant 1940). The latter was overcome by the use of screened cable and suitable earthing. The former was more troublesome and was only eliminated by winding a 'hum-bucking' coil round each geophone and shifting the phase of its current relative to that of the geophone.

As a check on the adequacy of the protection, and to ensure that the whole transducing and recording system was free from spurious electrical disturbances, it was the practice to record with the geophones clamped for 10 min or so before and after each experiment. There should then be no rise above valve noise level.

## 3. Preliminary results

Hill made a number of records, by day and by night, at Pendulum House, $1\frac{1}{4}$ miles north-west of Cambridge city centre. Each record lasted for several hours, and on at least one occasion for 24 h. He recorded the rectified output from two vertical geophones, one with a flat response from 12 c/s, upwards, the other flat from 25 c/s, the output being smoothed to give a time constant of about 1 s.

As might be expected near to a large city, and only $\frac{1}{4}$ mile from the nearest main road, the general level by day was found to be much greater than at night, by a factor of about 10 to 20. The day records showed considerable fluctuations the whole time, with a 'quiet' period at the lunch hour (13.15 to 13.45 h approx.) and a slackening in activity starting about 17.00 h and continuing up to about 01.00 h.

For the next 4 h there is a very steady background with occasional activity, the output commonly showing a gradual rise and fall, lasting 2 to 5 min; these 'peaks' were easily shown to be due to individual vehicles on the adjacent Huntingdon and Madingley roads. The night-time character of these records is shown in figure 1, plate 1, which was taken by the author later on, with a record of all three components. Two parts of the same record are shown. The vertical component differs markedly from the horizontals in places, an unexplained feature not confined to that particular night. Three traffic peaks appear close together in the top part and elsewhere, while the flat-topped feature in the lower part is the output from a motor working intermittently 150 yards away. At about 05.00 h the early traffic starts, the general level then rising continually till about 11.00 h. That this daylight rise is in fact man-made is proved by the 2 h lag on Sunday mornings, there being then no appreciable rise before 07.00 h.

Hill found the minimum level on calm, dry nights to be $1{\cdot}5 \times 10^{-6}$ cm/s r.m.s.* vertical ground velocity on the 25 c/s geophone, $3{\cdot}1 \times 10^{-6}$ cm/s on the 12 c/s geophone. This showed that most of the background energy lies in the lower frequencies. It was, therefore, clear that any further work should be done with geophones with as low a cut-off as possible.

## 4. Measurements round Cambridge

After the geophones had been modified to have a natural frequency of 4 c/s, the minimum background level at night at Pendulum House was found to be 5 to $6 \times 10^{-6}$ cm/s, a value rather higher than Hill's owing to the lower cut-off of the geophones. It was natural to inquire whether this background, with no wind or

* That the rectified output can be considered equivalent to the r.m.s. value has been justified by examining a.c. records taken in conjunction with rectified ones.

rain, was due to distant traffic, to machinery and other sources in the town, or to other than human causes.

The first was out of the question, owing to the infrequency of night-time traffic and the rapid fall-off as a vehicle recedes. This amplitude-distance relation will be discussed quantitatively in Wilson (1953). It was therefore decided to make some measurements of the background level round Cambridge, at a number of places up to about 6 miles from the city centre. These measurements were made by day, for convenience, and their object was twofold. First, the effects of the city's activity and distant traffic, by day, would be discovered. Secondly, it was hoped that the critical distance at which the city's effects disappeared in daytime would be found; a place could then be chosen beyond this distance where further work could be done by night without fear of the city's disturbance.

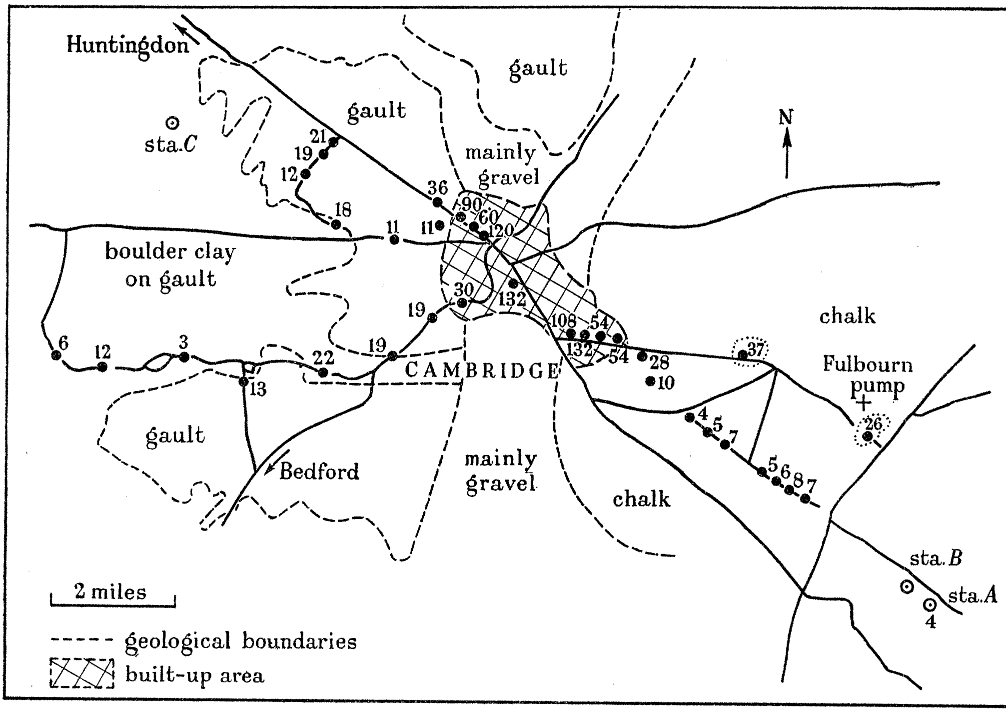


FIGURE 2. Background level of microseisms near Cambridge (daytime) in $\mu$cm/s.

Rectified records from one geophone, lasting 5 min, were made at each place. The procedure was to drive along one of the main exits from Cambridge, stopping every $\frac{1}{2}$ mile or so, and to place the geophone either on the pavement or on the side of the road. Except at stations very near the city there was usually 1 or 2 min when no vehicle was within $\frac{1}{4}$ mile, and the 'minimum mean level' (hereafter called the minimum or background level) was the mean value in the quietest 30 s period found. After one or two trials it was decided that inspection of this value was sufficient, and that a rigorous analysis was unnecessary. The results are shown in figure 2. All stations were occupied between 10.00 and 19.00 h on different days in July 1949.

The stations to the extreme west were on a quiet country road, and the group of seven stations to the south-east were on the Roman 'Road', little more than a cart-track, nearly a mile away from the nearest traffic. It is seen that the effect of the activity in the city is negligible at a mile or more from its outskirts, but that the effect, by day, of distant traffic, e.g. on the Bedford road, is considerable. It is considered that the geological structure, in this area at least, has no effect on the level, a conclusion supported in Wilson (1953). The values at the ringed stations are unduly high, the farther one being near the Fulbourn water pump, while the other was influenced by some unknown local machinery, the background consisting of a steady 50 c/s wave.

These measurements suggested that in order to study non-human sources, if such there be, it would be necessary to choose a place some 2 miles from the city or any large machinery, and at least $1\frac{1}{2}$ miles from a main road.

## 5. Measurements on the chalk

The next step was to record at such a place, over a period of several hours by day and by night, in order to investigate the diurnal variation, if present, and to determine the minimum level by night.

The place chosen, marked $A$ on figure 2, was about 300 yards west of the Balsham-Hildersham road, a minor road where the occasional passing car could easily be identified on the record. The nearest main road, Cambridge-Linton, is $1\frac{1}{2}$ miles away at its closest point.

Preliminary measurements in this area (see figure 2) had disclosed that the Fulbourn water pump was a powerful source of microseisms, interfering seriously with any sensitive measurements within a radius of 4 miles. Its properties are dealt with in Wilson (1953). It stops working, however, every Saturday night from 18.00 to 06.00 h, and the recording at station $A$ was mostly done on those nights.

One or three geophones were used. The geophones were dug in to a depth of 1ft. in a field with no crops and little grass. Chalk was found at 18 in. The first two records were made with one vertical geophone only, on Friday/Saturday 22.00 to 10.00 h and Saturday/Sunday 22.00 to 10.00 h, 22 to 24 July 1949. They showed a background level of $2 \times 10^{-6}$ cm/s on the first night and $6 \times 10^{-7}$ cm/s on the second night, the difference being due to the turning off of the pump. The daylight rise started at 07.00 h on Saturday morning; on Sunday, however, apart from the pump starting at 06.00 h, there was no rise till 09.00 h. Man-made causes other than the pump therefore probably determine the daytime level even at this comparatively remote locality. This level ($3 \times 10^{-6}$ cm/s) is, however, considerably lower than at Pendulum House.

The interesting feature of the second night, when the pump was silent, was that the background fluctuated very slightly the whole time, and superimposed on it were a number of 'pulses' or events, from a few seconds to $\frac{1}{2}$ min in duration. These had been noticed at Pendulum House, but could not be examined satisfactorily because of the rather high background.

Accordingly three vertical geophones were set up about 80 yards apart, roughly at the corners of a right-angled triangle. The object of this was to eliminate, by comparing the three geophone traces, all spurious 'kicks' which might be due to noise in the amplifiers or to purely local phenomena within the immediately subjacent soil. A certain amount of 'dither' in the amplifiers could not be eliminated despite scrupulous cleaning of terminals, valve-holders, etc., and in order to eliminate spurious disturbances arising from this cause, one amplifier (no. 1, top trace in figure 3, plate 2) was run off an entirely separate power supply. In this way, any event that appears both on no. 1 and either of the other two must have been genuine ground movement.

Figure 3 shows portions of the record taken in this way on the night of Saturday/Sunday 20/21 August, from 01.00 to 07.00 h. The events occur frequently, sometimes on all three geophones, at times on a pair or only on one. Shortly after 06.00 h the Fulbourn pump started, and all three geophones responded in a similar way, a valuable check on their uniform response to a distant source.

To account for these events, various possibilities present themselves. When appearing on only one trace, they were either electronic in origin or purely local to that particular geophone. In all other cases they must have been due either to the arrival of elastic waves from some source or to ground movement originating from stresses of some kind. If the event appeared on all three geophones, with the same amplitude, a distant source of elastic waves was a possibility; an example was the pump. But if two or three geophones were excited, to a different degree, there must either have been a local source of elastic waves, repeatedly varying in position, or differential ground movements of some other kind.

Wind, as a source of all the events, is improbable both on account of the sharpness of some of the pulses, and because of the arrangement of the geophones, nos. 2 and 3 being near the hedge and no. 1 70 yards from it. Agitation from the hedge would have shown great disparity between no. 1 and the others. Direct excitation was unlikely, as the geophones were properly buried and the cables laid flush with the ground. Nor can the movement of small animals be suspected, as they were confined to the hedge and its environments.

In order to investigate the frequency of arrival of distant earth tremors, another station ($B$) was set up (see figure 2) about $\frac{1}{3}$ mile north-west of $A$, along the Roman Road, and records made at $A$ and $B$ simultaneously, lasting about 4 h. During this time there were only two pulses that might be correlated.

A further record was made at station $A$, together with one at a station 2 miles along the Roman Road, to the south-east. Here there was no correlation between the records. These experiments confirm that few of the events recorded on 20/21 August were elastic waves from a distant source.

It may be held that many of these 'pulses' were electronic disturbances in the amplifiers that appear to synchronize on the record from time to time in virtue of their great number. In order to settle this question a statistical analysis was applied to a record made from 03.05 to 04.05 h on 13 March 1950.

A different site was chosen, in a quarry $1\frac{1}{4}$ miles south-east of Balsham, which was sufficiently far away from the Fulbourn pump to enable recording to be done on any fine night. The geophones were set up in a row, approximately 60 yards apart, and the amplifiers were run off three entirely separate power supplies. The recording was made at 0·25 mm/s, in order that events might be measured to within 1 or 2 s. The result is seen in figure 4, plate 3. Clamping of the geophones before and after was dispensed with on this occasion, as there was no intention of measuring the background.

The record has been analyzed in the following way. It is seen to consist as before of a number of movements or pulses superimposed on a more or less steady background. If, for each geophone, the amplitudes of the individual pulses are plotted

TABLE 1A. AMPLITUDES OF EVENTS AT BALSHAM QUARRY, GOG MAGOG HILLS, NIGHT 12/13 MARCH

| amplitude exceeded | | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| no. exceeded for geophone | 1 | 73 | 42 | 28 | 18 | 14 | 9 | 7 | 7 | 5 | 4 | 4 | 4 | 4 | 2 | 1 |
| | 2 | 44 | 19 | 11 | 8 | 3 | 2 | — | — | — | — | — | — | — | — | — |
| | 3 | 240 | 131 | 77 | 58 | 32 | 24 | 14 | 11 | 7 | 7 | 4 | 4 | 2 | 1 | — |

TABLE 1B. SIGNIFICANCE OF EVENTS FOR THE NIGHT 12/13 MARCH

| event | amplitude geo. 1 | amplitude geo. 2 | amplitude geo. 3 | % chance of fortuitous occurrence |
|---|---|---|---|---|
| 1 | 2 | 2 | 5 | $7\frac{1}{2}$ |
| 2 | 9 | 2 | — | 32 |
| 3 | 2 | 7 | 8 | 0·3 |
| 4 | 4 | 3 | 3 | 10 |
| 5 | — | 3 | 5 | 0·002 |
| | — | 4 | 15 | |
| 6 | — | 3 | 5 | 76 |
| 7 | 4 | 2 | — | 79 |
| 8 | 6 | 2 | — | 53 |
| 9 | 16 | 4 | 8 | 0·02 |
| 10 | — | 4 | 9 | 13 |
| 11A | — | 3 | 11 | 15 |
| 11B | — | 2 | 6 | 0·03 |
| | — | 5 | 8 | |

against frequency of occurrence, they are not found to belong to a Poisson or other simple distribution. They form some kind of a J-shaped distribution, but it was not considered worth while to fit them to such a one. Instead, the record has been split up into 820 intervals of 4 s each, and the maximum amplitude in each interval, for each geophone, has been measured in arbitrary units. The pulses have been classed in groups according to amplitude, and the results are seen in table 1A, each group being inclusive of the one following it. Only those movements which are perceptibly greater than the background have been classified. Those events which appear on two or more geophones simultaneously have been marked on the record, and by the probability of derangements, the chance of fortuitous synchronization has, in each case, been calculated.

The results are shown in table 1B. For events 3, 5, 9 and 11$B$ the chance is significantly small, showing that these pulses can definitely be attributed to ground movement. These include the event 5, lasting for 8 s, and 11$B$ in which one pulse is followed immediately by a second. Some of the events are of doubtful significance, and in others, namely, 6, 7 and 8, the coincidences are probably fortuitous.

As two of the significant events are recorded on two geophones only, while the other two show marked differences in those amplitudes, it may perhaps be fairly claimed that, even in the short space of 1 h, there is evidence of *local* earth movements. It will be noticed that in event no. 9, the amplitude on the centre geophone is less than on the flanks, suggesting that if it is an arrival from some local source, there is strong scattering or attenuation in certain directions, indicating a bodily rather than a surface wave.

## 6. Measurements on the Gault

To find whether these ground movements were a feature of the gault, as well as the chalk, a station $C$ (see figure 2) was set up $\frac{1}{2}$ mile south-west of the village of Lolworth, at a point at least $1\frac{1}{4}$ miles from any main road, and 1 mile from the nearest minor road.

The same arrangement of geophones was employed as at the Balsham quarry site. It was necessary to wait until 01.30 h before beginning recording, owing to the main road traffic. One hour's record was taken on 13/14 April 1950. It consisted of a steady background, with occasional pulses. Figure 5, plate 4, shows the 8 min run with geophones clamped, the calibration, and part of the record with geophones recording. The background level was $1{\cdot}0 \times 10^{-6}$ cm/s, about the same as that found on the chalk, but still well below that at Pendulum House.

As before, care was taken to run each amplifier off a separate power supply, and it will be noticed that in the clamping run there are no pulses that synchronize exactly. The geophones were buried flush with the surface, in a straight line 60 yards apart, in the centre of a field of short grass, and 60 yards from any bushes. There was no wind or rain, and there were no animals.

All the larger pulses in the part shown that synchronize exactly are marked. The ratios of the amplitudes, although varying slightly, are much nearer to unity than those found in the chalk. Even here, however, there is at least one event in which the centre geophone shows a small amplitude compared with the other two. In the remainder of the record the synchronous pulses are much less frequent.

## 7. Measurements away from Cambridge

It was desirable to make some measurements at other places in order to extend the field, and to test the effect of different geological conditions. Attention was concentrated on the remoter districts, sufficiently far from road or railway.

### 7·1. *Lakenheath*

At Lakenheath, about 30 miles north-east of Cambridge, there is sparsely populated country, although it is not possible to be more than 2 miles from the nearest road or railway. The superficial deposits are of very loose sand, typical of the Breckland, and very different from the sites hitherto studied. Difficulty was experienced, however, owing to the proximity of an aerodrome $1\frac{1}{2}$ miles away, and to the very intense animal life on the open heaths. It was out of the question to record in the woods because of the wind. No reliance therefore can be placed on any detailed interpretation of the records. It was found without doubt, however, that there is a diurnal variation here. The minimum level during the night was $1{\cdot}0 \times 10^{-6}$ cm/s, and was $2 \times 10^{-6}$ cm/s during the day. The site was occupied from 6 to 8 September 1949.

### 7·2. *Dartmoor*

This district was chosen in order to study microseisms on an igneous formation, as opposed to the sedimentary rocks of Cambridge. Dartmoor falls into two parts, north and south of the Tavistock-Ashburton road. As the northern half is higher and more exposed to the wind, as well as having a thicker covering of peat, it was rejected as a possible site in favour of the southern portion. Accordingly, on 11 September 1949, a position was occupied about 4 miles north of Ivybridge.

The mobility of this kind of expedition leaves much to be desired, as it is not advisable on Dartmoor to take a van and trailer anywhere off the track. A granite exposure could not, therefore, be reached, although in any case there appeared to be only perched boulders and inaccessible tors. There was no alternative but to accept the peat covering, and the geophones were embedded firmly in the peat, in a triangle formation 60 yards apart.

Two night records were made, on 11/12 and 12/13 September. A steady 15 miles/h wind was experienced on both nights. The minimum level was $1{\cdot}0 \times 10^{-6}$ cm/s, and there did not appear to be any daylight rise, although recording continued until 07.30 h. There was, however, much more fluctuation on the records than on previous occasions, and it is suspected that most of the activity was due either to wind drag on the heather which was about 2 ft. high, or to the trickle of water through the peat. As the wind strength did not vary, it was impossible to correlate it with the microseisms.

On 13 September there was a heavy storm, and it was decided to abandon the position and move on to Salisbury Plain.

### 7·3. *Salisbury Plain*

With the kind permission of the military authorities a station was established in a small hollow near Long Barrow, about 5 miles north-west of Larkhill. This was well isolated, at least 3 miles from any road or camp except for a military track crossing the Plain which ran within a mile of the station; this was only used two or three times during the occupation, and vehicles on it were immediately noticeable. The station was occupied from 17 to 20 September 1949, during which time there were no manoeuvres or firing of any kind in the eastern part of the Plain.

Here meteorological conditions were good, and the geophones were placed at the corners of a right-angled triangle, approximately 100 yards apart. Figure 6, plate 4, shows a trial record taken at 18.00 h and brings out clearly the small background level.

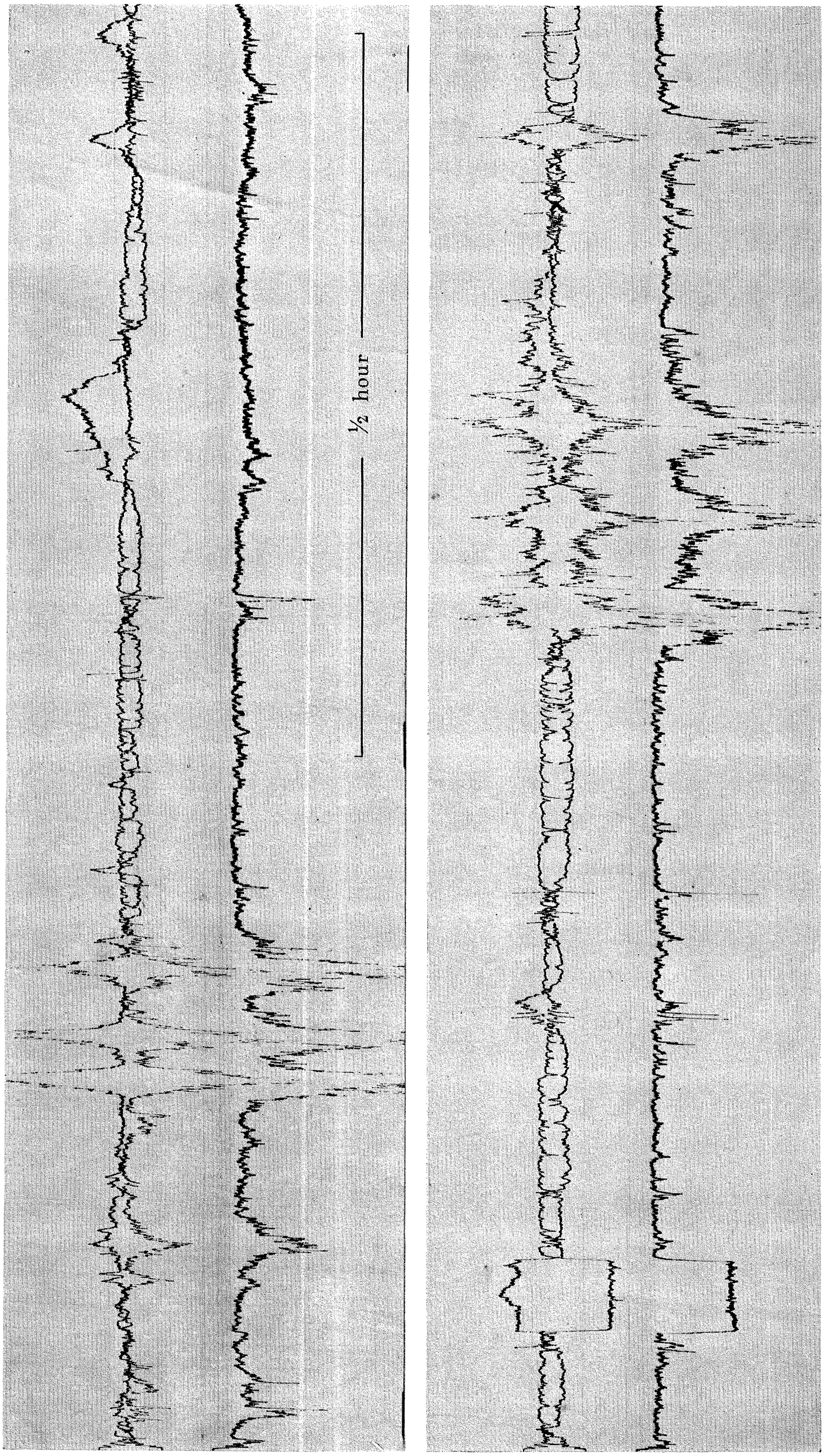


FIGURE 1. Rectified output from three components (reading downwards, vertical, horizontal SW and horizontal SE) at Pendulum House (night-time).

(*Facing p.* 184)

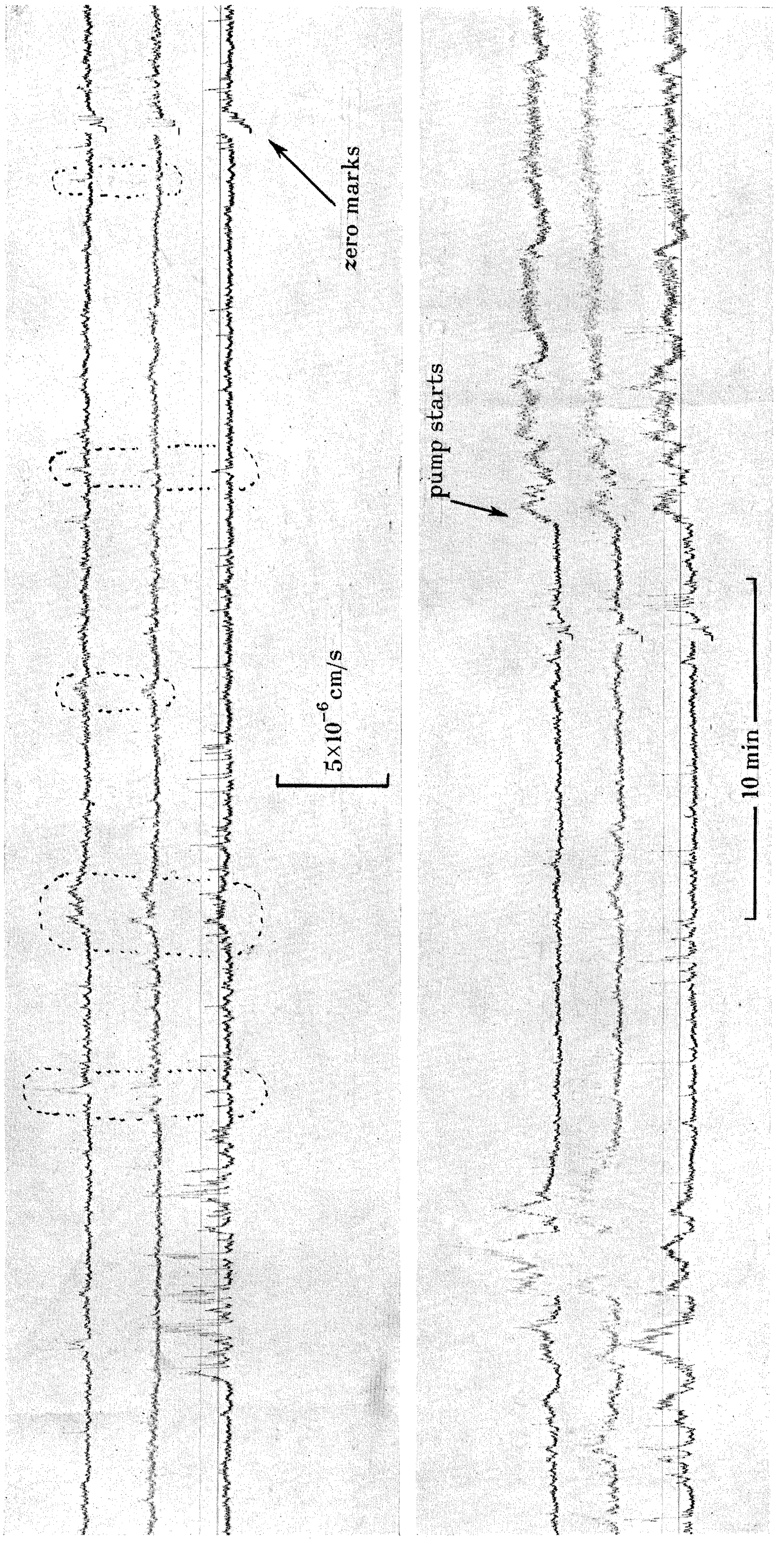


FIGURE 3. Rectified output from geophones 80 yards apart at station *A*, Gog Magog Hills (night-time).

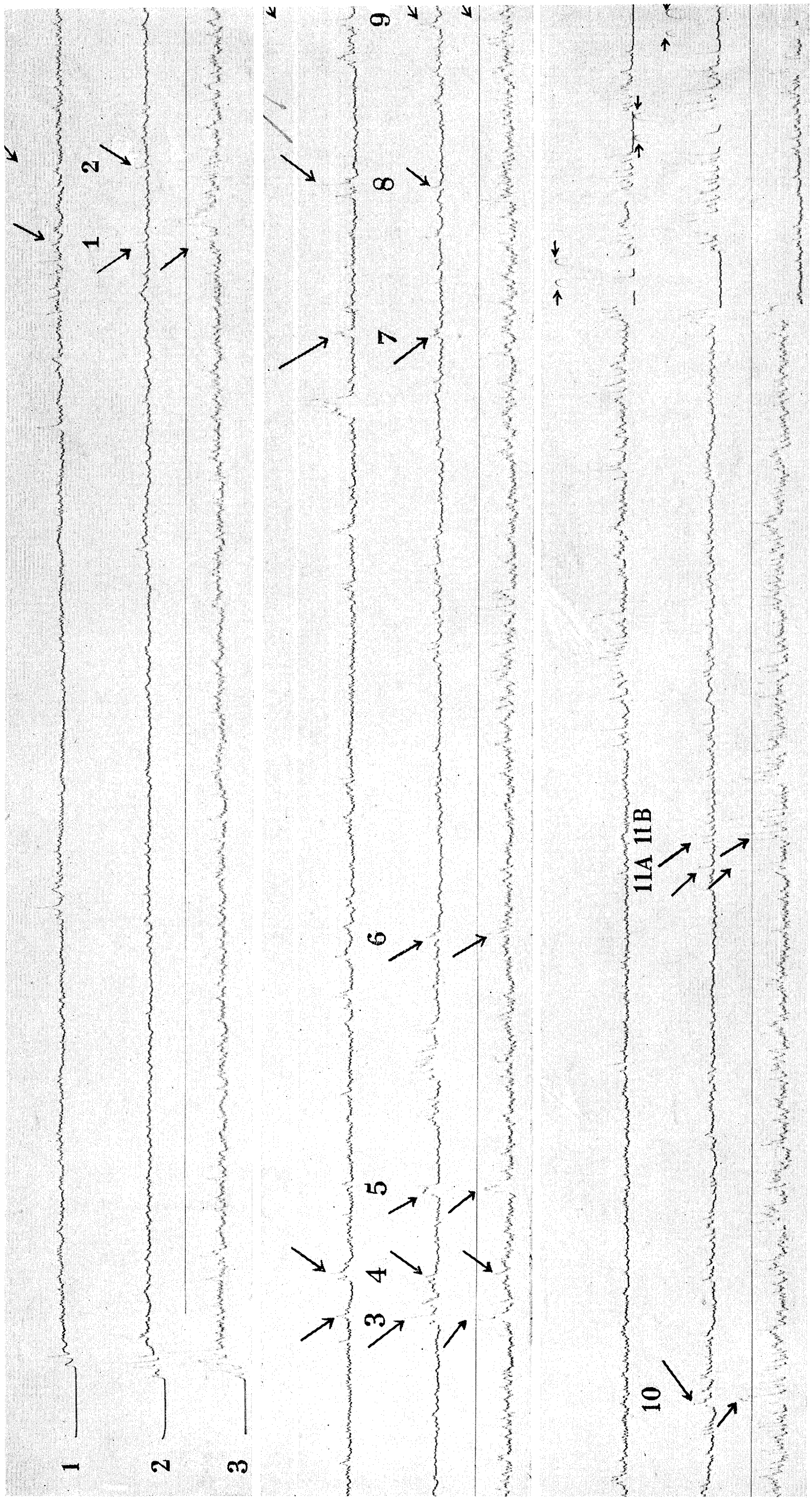


FIGURE 4. Rectified output from three geophones at Balsham Quarry, Gog Magog Hills (night-time), 12/13 March 1950. The pulses indicated by horizontal arrows represent calibration input of $1\,\mu$V.

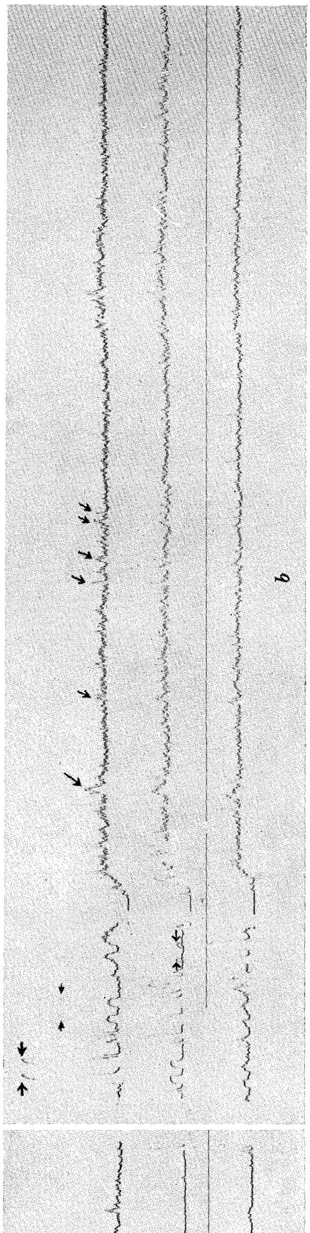


FIGURE 5. Rectified output from three geophones at Lolworth, Cambridge (night-time): *a*, geophones clamped; *b*, geophones in action.

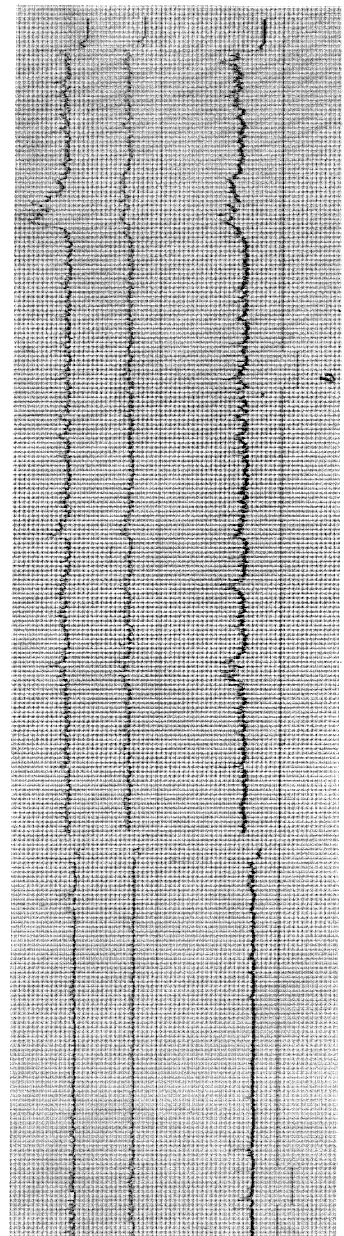


FIGURE 6. Rectified output, Salisbury Plain, showing difference between (*a*) valve noise and (*b*) background level (evening).

The next record was made from 03.12 to 09.50 h. This period was chosen in order to test the 'daylight rise' effect. No such rise was found, the background level remaining at approximately $6 \times 10^{-7}$ cm/s for the whole period. This constitutes definite evidence that at least one place can be found in England where short-wave microseisms are due entirely to natural causes.

The pulses or events were very similar to those found at Cambridge. Short wave-trains were sometimes seen on a cathode-ray oscilloscope. No conspicuous frequency was observed. A further record was made, with one geophone and the frequency analyzer (described in Wilson 1953). This showed that the average spectrum of the pulses covered the range of all frequencies between 6 and 60 c/s, although the spectra of individual pulses differed considerably. It was not possible to determine the spectrum of the background owing to its low level.

## 8. Other sources

The other main sources of microseisms not so far discussed are aircraft, machinery and meteorological causes. The first is of no particular interest except inasmuch as the effect is more marked on the vertical than on the horizontal recording geophones; the frequency is nearly always between 70 and 90 c/s.

Machinery and other human activity are very noticeable. The microseismic strength depends largely on how the vibrating system is coupled to the ground. Microseisms from the Fulbourn water pump will be discussed in Wilson (1953).

There remain the effects of wind and rain. The former does not impede operations as much as seems to have been supposed. A short experiment was made at Pendulum House with two geophones. One was buried underneath a tree in a field, while the other was buried 30 yards away in the centre of the field. Both were operated simultaneously for several hours during the day, while there was a 20 miles/h wind with gusts up to 30 miles/h, shown on a wind gauge. The geophone under the tree registered an average of 0·9 to $1{\cdot}2 \times 10^{-4}$ cm/s, while the other recorded only $0{\cdot}3 \times 10^{-4}$ cm/s. The next day, when the wind had dropped to 7 to 10 miles/h, the respective means were 0·3 to $0{\cdot}6 \times 10^{-4}$ and $0{\cdot}3 \times 10^{-4}$ cm/s. This shows that a geophone, if properly buried at least 30 yards away from any tree or building, shows very little response to wind.

For normal purposes, therefore, it is sufficient to bury the geophone so that its top is flush with the surface of the ground. On Salisbury Plain, however, it was found that a geophone so buried showed a background level of $10^{-6}$ cm/s when there was a slight breeze. Burial at a depth of 2 ft. showed a distinct fall to $6 \times 10^{-7}$ cm/s.

Little detailed work was done on the effect of rain. Experience showed that rain always substantially increased the microseismic level. The level due to rain varied with circumstances, but as an indication of its effect, it was found that when the top of the geophone was buried 6 in. below the surface light rain produced perhaps $6 \times 10^{-6}$ cm/s, and heavy rain of the order of $3 \times 10^{-5}$ cm/s.

## 9. Discussion of results

Under the limited conditions in which these experiments have been carried out the different sources of the short-wave microseisms have been analyzed, and their relative importance found. It now remains to discuss the nature of the small ground movements, the background which still remains after all human sources have been excluded, and to decide whether these two are related in any way.

It is convenient here to summarize the background levels obtained by day and by night at the different sites occupied. All values in table 2 are those obtained after correction for the valve noise. It is to be noted that the night background level at Pendulum House varied from night to night by a factor of about 2. The background day level there is only reached at the rare moments when there is no car within about $\frac{1}{2}$ mile. The mean levels show, of course, a much higher diurnal variation, the day mean level being about 300 to 1000, while the night mean level is not very different from the background level. The 'valve noise', which is the recorded level when clamped, is compounded from the thermal fluctuation due to the resistance of the geophone, its damping resistance and the input transformer primary and secondary, and from the 'shot' noise in the first valve of the amplifier. The thermal fluctuation component is only $0{\cdot}02\,\mu$V, which is equivalent to an r.m.s. ground movement of $1{\cdot}2 \times 10^{-7}$ cm/s. The remainder is due to noise from the first valve.

Table 2. Microseismic background levels

($10^{-7}$ cm/s r.m.s. vertical ground velocity.)

| site | geological formation | night level | day level |
|---|---|---|---|
| Pendulum House, Cambridge | gravel on gault | 30 to 60 | 110 approx. |
| Gog Magog Hills, Cambridge | chalk | 6 to 9 | 30 to 40 |
| Lolworth, Cambridge | gault | 10 | — |
| Lakenheath | sand on chalk | 10 | 20 |
| Dartmoor | peat on granite | 10 | 10 |
| Salisbury Plain | chalk | 6 to 9 | 6 to 9 |
| (valve noise, etc. | | 3 | 3) |

At all the sites the level is significantly higher than the valve noise, a fact which is immediately obvious from inspection of figure 6, where the level was the lowest reached. Careful consideration has been given to the possibility that the lowest background level ($6 \times 10^{-7}$ cm/s) is due entirely to instrumental causes. Wolf (1942) has shown that the r.m.s. voltage $\overline{V}$ due to the Brownian movement of the mass of a geophone is given by $\overline{V}^2 = \dfrac{2R^2}{R+r}\,\boldsymbol{k}T\omega_0$, for a critically damped detector, where $R$, $r$ are geophone and damping resistances, $\boldsymbol{k}$ is Boltzmann's constant ($= 1{\cdot}38 \times 10^{-23}$ joules/° K), $T$ is absolute temperature, $\omega_0/2\pi$ is the natural frequency. It is found that $\overline{V} = 0{\cdot}0056\,\mu$V, a value which is about 10 times too small to explain the results.

Movement of the geophone coil due to creep in the supporting helical spring is also an inadequate cause. An increase of 3 cm/year in its extended length would, given movement in sufficiently rapid discrete 'jerks', be required to produce a background level of $10^{-7}$ cm/s. Temperature changes, although capable of moving the geophone coil appreciably and of causing the other components to creak, could not sustain a constant background level over any length of time. These might account for some of the individual pulses observed, but not of course for those observed simultaneously on two or more geophones.

The background, therefore, as well as the pulses, is due to some external cause.

Under the heading of distant sources may be considered earthquakes and long-period microseisms. It is most unlikely that near earthquakes or fault movements occur frequently enough to account for the steady background, or for all the pulses. Long-period microseisms, although continuous and of large amplitude, fall quite outside the spectrum recorded.

It is considered, therefore, that rather local earth movements are the cause of both the pulses and the background, though it is not necessary to postulate the same kind for each phenomenon. Nor is it clear whether the movements are a direct strain due to stresses in the crust, or whether they are elastic waves transmitted from some local sources. They may be analogous to the 'creaking' which is heard in mines. Considerable further work on different geological formations and at different depths below the surface would be necessary to determine their exact nature.

Various causes may be suggested. If a rock such as chalk is stressed sufficiently, movement may occur along the fissures and joints. Indeed, the formation of joints is commonly thought to be due to stressing. Compaction may be the cause, and it is easy to show that the power needed to produce both pulses and background could be obtained from a very small rate of compaction, provided it were sufficiently continuous. The pulses and background may originate from the same sources, if these are randomly placed over a wide area near the surface, and vary randomly in position and time. The few sources near the geophone would then create the rather irregular pulses, while the integrated effect from a large area would produce the steady background. The same argument could be used to account for the very similar type of record obtained during a shower of rain.

Other possible mechanisms are temperature changes at the surface, water movement in the zone of intermittent saturation, and dilation due to adsorption of water. The first is unlikely, as the Salisbury record showed no increase in activity in the morning. Water movement is possible, especially in the chalk, but again unlikely in the dry summer of 1949. Dilation in the gault clay is more than a possibility, as the forces involved have been known to displace large engineering structures; but it would leave the chalk movements unexplained.

One other possibility deserves to be mentioned. Earth tides cause the earth's surface to move through a few inches in 6 h, and only very small departures from a smooth movement would be sufficient to cause the background level. These irregularities would, again, have to occur with a frequency of the same order as the natural frequency of the geophone, and they might be found in the elastic after-working of the earth's mantle as it undergoes a continually changing stress. It may be possible to account also for the pulses in this way, if the tides cause sufficient differential movement of the ground.

The presence or absence of a diurnal variation of background is largely governed by traffic conditions. If there are only minor roads within 2 miles of the site there are likely to be periods during the day when there is no car within 2 miles, and the conclusions reached in this and the subsequent paper are that this is about the farthest distance at which a vehicle is perceptible. There will then be no diurnal change in background level, but only a number of traffic 'peaks' during the day. But if the site is within $1\frac{1}{2}$ to 2 miles of a major road of sufficient traffic density, then there will always be one or more vehicles within a distance of 2 miles, and the day background will always be higher than at night.

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# An analysis of the vibrations emitted by some man-made sources of microseisms

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[Plate 5]

Study of the vibrations from traffic and machinery shows that most of the man-made microseisms are in the 4 to 10 c/s range, at least near Cambridge. Examination of traffic microseisms shows that surface waves predominate at 200 yards or more from the source. Their frequency depends more on geological conditions than separation of source and observer. Microseisms from a waterworks pump were recorded up to 4 miles away, and consisted of bodily waves of 15 to 42 c/s frequency, and surface waves of 7 to 10 c/s which predominated at distances greater than $\frac{1}{2}$ mile from the pump.

It is concluded that the bulk of microseisms are surface waves from traffic and machinery, but their attenuation renders them insignificant in most cases at a distance of 2 miles.

## 1. Introduction

In the preceding paper the origins and nature of microseisms in the frequency range 4 to 100 c/s have been discussed for some localities near Cambridge and at other

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