increased. Although much remains to be discovered, it is clear that the past five years have seen the unveiling of many of the most interesting physical phenomena of Antarctica.

The development of research in Antarctica during the International Geophysical Year was so successful that the International Council of Scientific Unions decided that it should encourage the continuation of an international programme in Antarctica after the conclusion of the International Geophysical Year. The Special Committee on Antarctic Research was set up for this purpose, and international co-ordination of Antarctic programmes is still continuing under the auspices of the International Council on this basis.

In his article, Dr. Robin describes a number of the achievements of the past five years in the disciplines of meteorology, geomagnetism, upper atmosphere physics, glaciology, crustal investigations, oceanography, cartography and biology. Much remains to be done to complete the straightforward exploration of the interior of the continent, and to collect sufficient data for the thorough analysis of scientific problems at present under investigation. More fields needing investigation are apparent, and the present work will reveal still further horizons. So long as expeditions to Antarctica continue to concentrate on fields of study which cannot be undertaken at less cost in more accessible lands, support for such efforts will be justified. Even so, the general public and Governments may look for direct financial returns on their antarctic investments in terms of rich mineral deposits or other forms of wealth. Such returns may not be impossible, but it would seem a short-sighted policy to stress this aspect too much in obtaining support for long-term investigations. Although its value may not always be obvious, research in Antarctica must be viewed as offering the type of return one may expect from pure rather than applied science. By adding to the whole field of physical and biological knowledge of our globe, this research may well help to uncover some basic truths.

SUB-ACOUSTIC WAVES FROM LARGE EXPLOSIONS

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THE Krakatoa volcanic explosion of August 27, 1883, gave rise to repeated barographic disturbances all over Earth, from which it was possible to plot the development of the wave-front of the atmospheric pressure wave resulting from the explosion. This wave went around Earth three times before it became too weak to affect barographs of normal sensitivity; the data are available in the *Report of the Krakatoa Committee of the Royal Society*[1]. Typically, the disturbance on its first passage over Earth was reported to consist of a sudden pressure rise, followed sometimes by oscillations, and then by a deep depression and a further rise; the whole phenomenon took about 1 hr. The velocity of the waves over Earth varied in different directions, and at different times in the same direction, between the limits of 674 and 726 m.p.h. The direct wave from Krakatoa to Europe took times of 36 h. 24 m., 36 h. 30 m. and 36 h. 50 m. to encircle Earth on successive transits. The wave that reached Europe by the path through Krakatoa's antipode took times of 34 h. 46 m. and 35 h. 04 m. for its two complete recorded circuits. The difference in velocity in the forward (westward) and reverse (eastward) directions was presumably due to the effects of upper atmospheric currents.

The disturbance that originated in Siberia on June 30, 1908, also gave rise to strong atmospheric waves which were recorded on microbarographs in many parts of the world. Kulik[2] appears to say that this wave "travelled twice round the world"; but the data published by Whipple[3] indicate that the most distant recording was that made at the Potsdam Observatory, which alone recorded the antipodal wave as well as the direct one, and there is no suggestion that either wave was detected anywhere more than once. The peak amplitude of the direct wave at Potsdam was thought to be about 760 microbars and that of the antipodal wave 170 microbars. Whipple[4] gave a diagram compiled from the records at several stations in Britain, indicating the structure of the disturbance (Fig. 1); he stated that the velocity of the front of the disturbance was 323 m./sec., and that of the main trough 318 m./sec. This compares with a mean velocity of about 315 m./sec. for the Krakatoa waves.

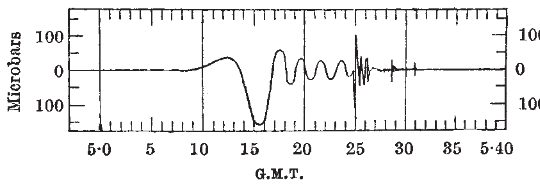

Fig. 1. Microbarographic disturbance in Britain on 30.6.08, after Whipple

The Russian nuclear explosion of October 30, 1961, is thought to have been of more than 50 megatons TNT equivalent, and to have occurred in the Novaya Zemlya region at about 0830 G.M.T. This explosion gave rise to a strong atmospheric wave, which was widely detected. At Aberdeen it was recorded on two microbarographs of a new design, details of which will be duly published. Mr. S. T. Forbes has helped with their design, construction, and calibration. The instruments are differential ones, capable of a recording sensitivity of 0·1 microbar per division. They are normally operated at one-tenth or less of this sensitivity, since atmospheric conditions are rarely steady enough to justify more; the instruments can be made insensitive to very rapid and very slow disturbances, and they were set to respond uniformly to disturbances with periods between about 25 sec. and 10 min. Local atmospheric conditions were unfavourable at some of the relevant observation times, and other stations may well have obtained better records; but the Aberdeen records are reproduced here in the hope that they may be of some general interest.

On the first passage of the direct wave (Fig. 2), the atmosphere was locally disturbed, giving a 'noisy' background. The disturbance from the explosion,

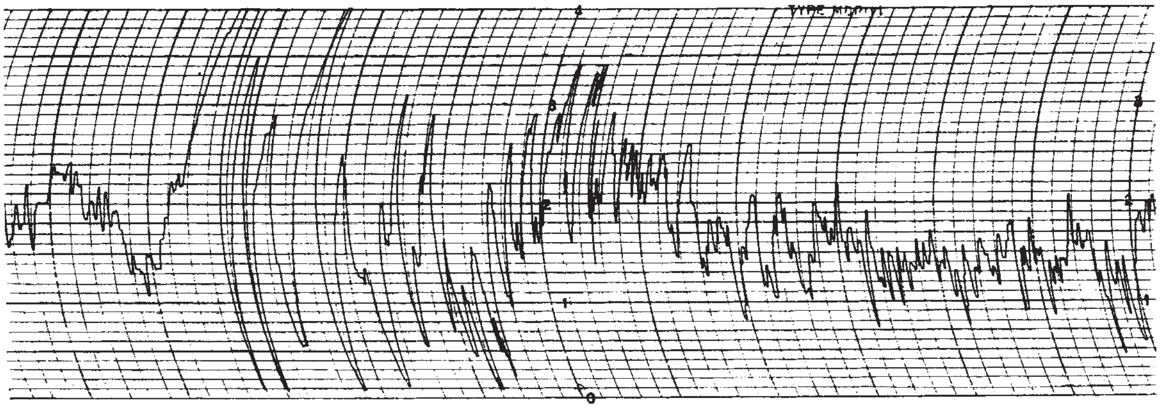

Fig. 2. Microbarograph record at Aberdeen, 30.10.61. Numbered ordinate at 1200 G.M.T.; chart speed, 1 small horizontal division = 2 min. Full-scale vertical deflexion = 400 microbars

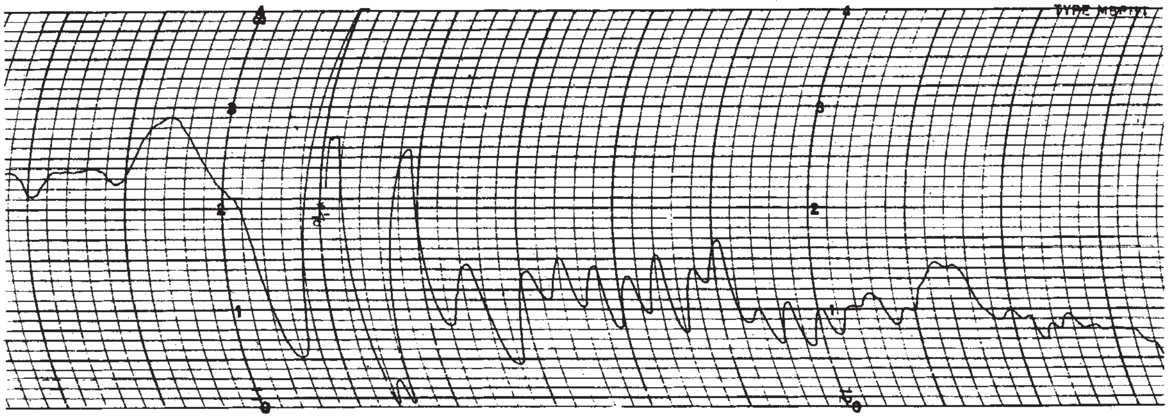

Fig. 3. Microbarograph record 31.10.61. Numbered ordinates at 1700 and 1800 G.M.T. Full-scale deflexion before 1710 G.M.T. = 400 microbars; sensitivity halved after 1710 G.M.T.

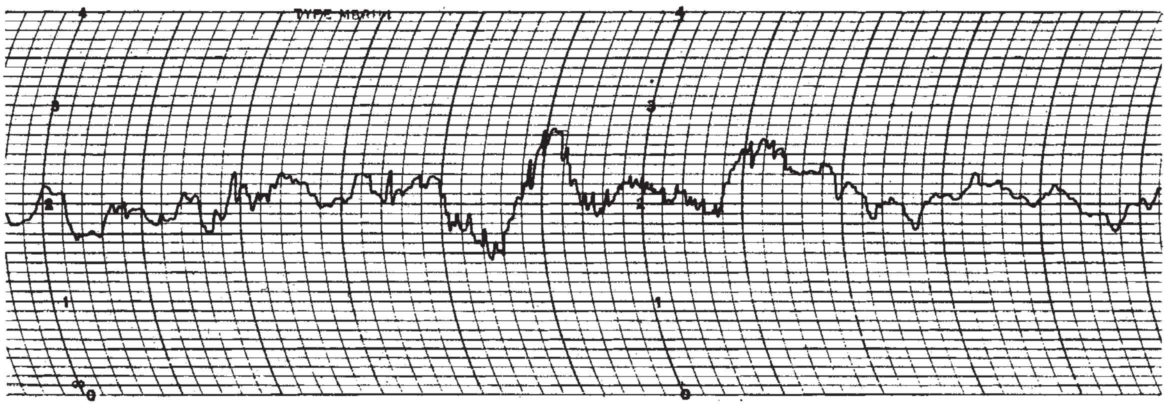

Fig. 4. Microbarograph record 31.10.61–1.11.61. Numbered ordinates at 2300 and 2400 G.M.T. Full-scale vertical deflexion = 800 microbars

some 2,000 miles distant, began to arrive at about 1123 G.M.T., the immediate effect being a pressure rise which took the recording pen off scale. Four minutes later, this was followed by a very sharp fall, the trough occurring at 1129 h.; the recording system was so arranged that negative deflexions were in effect rectified, and thus were recorded as positive, to give the equivalent of using a recording chart of twice the width. The trough therefore appears as a peak on the record, interposed between the first two genuine peaks at 1127 G.M.T. (off scale) and 1136 G.M.T. The maximum peak to trough amplitude was about 1,000 microbars. Thereafter there was a succession of waves, decreasing in amplitude and period; about twenty of these could be identified, the last being at 1228 G.M.T. and having a period of less than 2 min., as compared with 4 min. for the first wave.

At 1702 G.M.T. on October 31, 1961, a strong wave began to arrive, presumably from the opposite direction, and having travelled over the antipode of Novaya Zemlya in Antarctica. Fig. 3 shows this wave-train—the sensitivity of the recording system was halved at 1710 G.M.T. to keep the recording on scale. The first effect appears to have been a pressure fall (unless the rise starting at 1650 G.M.T. was in fact part of the same train), and the maximum peak-to-trough amplitude was about 580 microbars. This train was therefore surprisingly strong, being more than half the amplitude of the direct wave, after having travelled about 23,000 miles. The record is in fact clearer than that of the direct wave, since the local conditions were quieter. About twenty-six peaks can be distinguished, the last being at 1828 G.M.T.; there is evidence of dispersion, but it is surprising how well the wave-form has been preserved, the earliest wave to arrive having a period of 9 min., and the last less than 2 min. The focusing in the neighbourhood of the antipode must have been appreciable.

At about 2340 G.M.T. on the same day, a disturbance was recorded that may have been due to the wave re-diverging from Novaya Zemlya after encircling Earth (Fig. 4). The wave-form was much degraded, with a maximum peak-to-trough amplitude of about 220 microbars. It is, however, well above the local fluctuations at the time, and no other disturbance of such magnitude arrived between 2100 G.M.T. on that day and 0300 G.M.T. on the following day. These limits are well outside the scatter of times to be expected on the Krakatoa evidence, and it thus appears that if the direct wave was detected at Aberdeen on its second transit (and from the magnitude of the antipodal wave 6 hr. before, it should have been) the disturbance beginning at 2340 G.M.T. was the result. This gives a time of 36 h. 17 m. for a complete passage round Earth.

A strong disturbance was detected at 0422 G.M.T. on November 2, which could have been due to the second passage of the indirect wave (Fig. 5). The maximum amplitude was about 200 microbars, and the wave-form was again much degraded. Similar degradation on a larger scale had been observed on the Krakatoa waves. If this disturbance was in fact due to the explosion, the time for the first complete reversed circuit from Aberdeen was 35 h. 20 m.

At 1100 G.M.T. on the same day, another strong disturbance was detected (Fig. 6). This was of a similar form to that received at 2340 h. on October 31 and of amplitude 160 microbars. If it was due to the third passage of the direct wave over Aberdeen, the time for the second complete forward transit would have been 35 h. 20 m., nearly 1 hr. shorter than that for the preceding transit. While such a variation is surprising, the 1100 G.M.T. disturbance was unmistakably the largest within the bracket of times at which the wave would have been expected back at Aberdeen, and it occurred when local conditions were fairly quiet. There was a small disturbance of amplitude 100 microbars at 1144–1210 G.M.T., when the signal had been expected; if this was in fact the wave from the explosion, the time for the second encirclement was 36 h. 04 m.

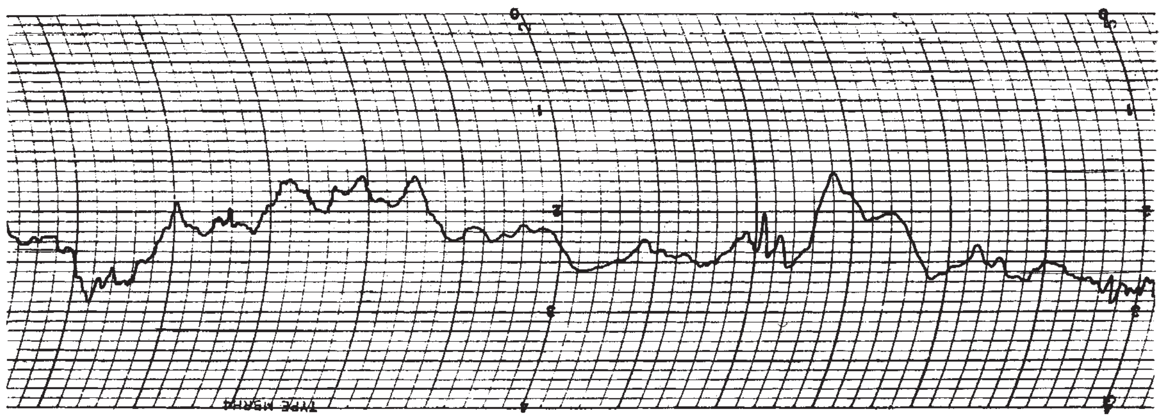

Fig. 5. Microbarograph record 2.11.61. Numbered ordinates at 0400 and 0500 G.M.T. Full-scale vertical deflexion = 800 microbars

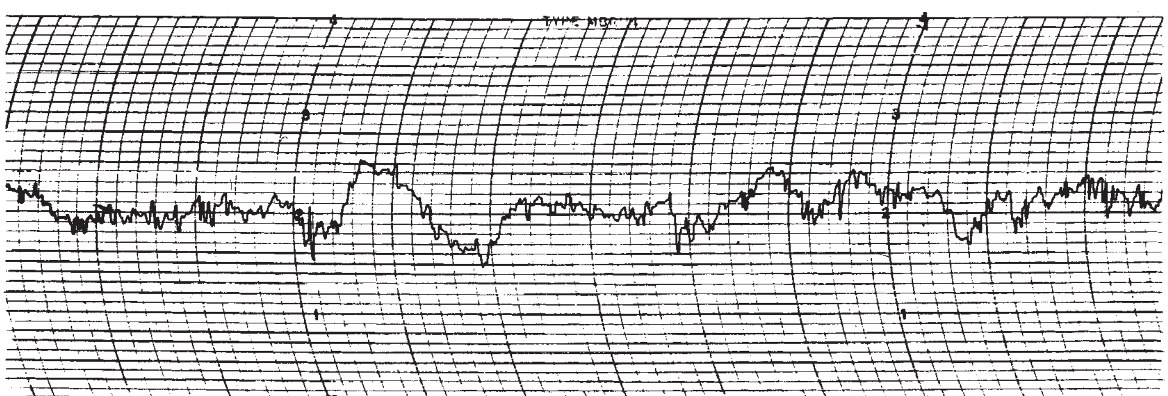

Fig. 6. Microbarograph record 2.11.61. Numbered ordinates 1100 and 1200 G.M.T. Full-scale vertical deflexion = 800 microbars

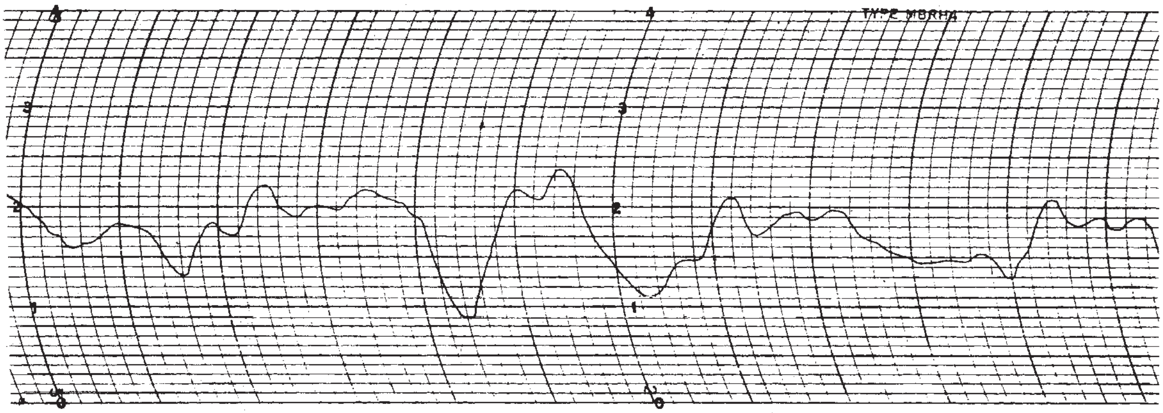

Fig. 7. Microbarograph record 5.11.61. Numbered ordinates 0900 and 1000 G.M.T. Full-scale vertical deflexion = 400 microbars

On November 3, conditions were very disturbed, with snowstorms over north Scotland, and no recognition was possible. The fourth passage of the reverse wave would have been due at about 0330 G.M.T. on November 5, if the times for the second and third transits had been the same as that for the first. Local conditions were quiet at this time, but no disturbance was observed. A wave-train lasting about 100 min. after 0440 G.M.T. was recorded; but there is no reason to associate this with the previously observed passages. A wave-form arriving at 0940 G.M.T. on November 5 bore some resemblance (Fig. 7) to the disturbances observed on previous passages; the amplitude was about 120 microbars. If this was due to the explosion on October 30, it would have represented the fifth passage of the direct wave over Aberdeen, giving an average of 35 h. 20 m. for the third and fourth encirclements. The evidence, however, is slender.

The times of passage of the first and second direct and reverse disturbances over Aberdeen can be used to estimate the time of the explosion and its distance from Aberdeen. The former comes out to be 0829 G.M.T. and the latter 1,990 miles. This estimate allows for the apparently different velocities of the forward and reverse waves. Rather cruder estimates, not making this allowance, give explosion times of up to 6 min. earlier and distances up to 90 miles greater.

As regards scale, the explosion produced a disturbance of amplitude about three times as great as that registered after the large explosion of October 23. The time between the first two peaks caused by that explosion was about 4 min., compared with 6 min. for that of October 30.

The most remarkable point about the Aberdeen records is the strength and clarity of the first antipodal wave, which had more than 50 per cent of the amplitude of the direct wave. It is not yet known whether this was a common experience, or whether it was due to unusual propagation conditions. The comparison of the wave-form with that observed after the 1908 incident, while showing some similarities, indicates that the latter had an extra train of short-period waves at the tail of the main train. This feature of the 1908 incident was recorded at several stations in England. Whipple suggested that the main train was due to the bow wave of a meteorite as it fell through the atmosphere, while the later train was caused by the impact of the meteor with the ground. Both trains are thought to have originated almost simultaneously, and to have become separated by atmospheric dispersion, the shorter waves travelling more slowly. On this view, they could even have originated slightly earlier than the longer waves of the main train, and it would be permissible to identify the shorter waves with the shock caused by the meteorite traversing the atmosphere; the main train could then have been caused by the meteorite exploding in the lower atmosphere.

It is possible to estimate the minimum mass of a meteorite sufficient to have caused the Siberian incident. The amplitude of the pressure wave over Britain in 1908 was about 200 microbars, the range being 5,700 km.; at Slutsk, 3,740 km. from the incident, the amplitude was about 300 microbars. The nuclear explosion of October 23, 1961, near Novaya Zemlya, thought to have been of 30 megatons TNT equivalent, produced an amplitude of about 350 microbars at Aberdeen, about 3,200 km. distant. The 1908 incident thus appears to have released energy of about 30 megatons equivalent; Penney *et al.*, using the statement of Whipple[3] that trees had been continuously felled to 20 km. radius, estimated the energy release as 13 megatons equivalent. Kulik[2], however, reported that continuous windfall of trees extended "from the centre to distances up to 30 km.", and that traces of burns were visible out to "15 to 20 km."; this evidence might double Penney's estimate.

Taking the 1908 energy release as being of 30 megatons equivalent, within a factor of two either way, and assuming that 1 gm. of TNT gives about 4×10^{10} ergs, the release was thus about 10^{24} ergs. Scorer[6], incidentally, estimated the release as about 5×10^{24} ergs. on the microbarographic evidence prior to 1950. Radio-astronomical evidence strongly indicates that the maximum velocity for meteorites entering Earth's atmosphere is about 80 km./sec. (consistent with the view that all observed meteorites are members of the solar system). Assuming that the Siberian incident was due to a meteorite member of the solar system, and that the air waves were caused by its kinetic energy alone, its mass was probably at least 30,000 tons.

[1] *Rep. Krakatoa Comm. Roy. Soc.*, edit. by Symons, G. J. (Trübner and Co., London, 1888).
[2] Kulik, L. A., *C.R. Acad. Sci. U.R.S.S.*, **22**, 515 (1939).
[3] Whipple, F. J. W., *Quart. J. Roy. Met. Soc.*, **60**, 505 (1934).
[4] Whipple, F. J. W., *Quart. J. Roy. Met. Soc.*, **56**, 287 (1930).
[5] Hunt, J. N., Palmer, R., and Penney, Sir William, *Phil. Trans.*, **252**, 275 (1960).
[6] Scorer, R. S., *Proc. Roy. Soc.*, A, **201**, 137 (1950).