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A WORLDWIDE STORM OF MICROSEISMS WITH PERIODS OF ABOUT 27 SECONDS

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ABSTRACT

On 6 June 1961, a storm of microseisms with periods of about 27 seconds and a duration of about 8 hours was detected by long period seismographs throughout the world. At Palisades, ultra-sensitive seismographs detected the storm for an interval of about 2 days during which the periods of the waves decreased from about 28 to about 20 seconds. The seismic waves appear to be largely of the Rayleigh type and seem to originate in the southern or equatorial Atlantic Ocean.

The favored hypothesis on the nature of the source mechanism suggests that the seismic waves were generated by dispersed ocean waves striking the coast of the Gulf of Guinea. A second hypothesis suggests that the microseisms are a form of harmonic tremor associated with magmatic activity beneath the South Atlantic Ocean.

Introduction

On 6 June 1961, between about 1200 GCT and 2000 GCT, a storm of microseisms with periods of about 26 to 27 seconds was detected by long period seismographs at many locations throughout the world. No storm of such widespread proportion has ever before been reported. Even though the sensitivity and the geographical distribution of long period instrumentation, and consequently the ability to detect such a storm, has improved markedly in recent years, this event is so prominent at some stations that it seems unlikely that similar events have been very frequent in the recent past. There may, however, have been storms of similar nature but smaller size which have gone unnoticed, for many storms of long period microseisms have been observed at individual stations.

In addition to its widespread distribution, this storm is unusual and outstanding in certain other respects. The periods, 26 to 27 seconds, of the waves are considerably longer than the periods of microseisms normally observed, even on the few seismographs operating with high sensitivity in this period range. On such instruments the background noise usually is made up of waves with periods of about 20 seconds or less. For less specialized long period seismographs, the background noise consists of ordinary microseisms corresponding to the well-known peak of the earth noise spectrum between about 3 and 10 seconds (Brune and Oliver, 1959).

The duration of the storm of 6 June, only a few hours at most stations, is much less than the duration of most microseismic storms. Ultra-sensitive instruments at one station show that this storm actually had a considerably longer duration, but the interval when the amplitudes were very large is very brief. During this interval the bandwidth of the frequency spectrum is apparently much narrower than in ordinary storms. Whereas the length of a beat in an ordinary storm is usually 5 to 10 cycles, the beats of the 6 June storm were sometimes as long as 40 or 50 cycles.

The 6 June storm also has the property that the periods of the waves decrease gradually throughout the entire duration. At most stations where the storm was observed only for a few hours, the periods of the waves decreased from about 27 seconds to about 26 seconds. At Palisades, where ultra-sensitive instruments are operated, the storm began slightly earlier with periods of about 28 seconds and continued through the interval of large amplitudes for about 2 days until the periods were less than 20 seconds. The gradual decrease of period with time is quite certain wherever observations are good, but the experimental error in measuring the exact period at any given time and the slow variation of period with time prevent a precise determination of the velocity of propagation of the microseisms between distant stations. However, the arrival times are never inconsistent with propagation between stations as seismic waves.

On the basis of particle motion studies, the seismic waves appear to be predominantly of the Rayleigh type, although some Love waves may be present as well. When the waves are of the Rayleigh type the direction of the approach can be determined, and by combining such results from several stations the source of the seismic waves can be localized. The 6 June storm appears to have originated in or near the southern or equatorial Atlantic Ocean, possibly in the general vicinity of the Gulf of Guinea.

The mechanism of generation of the seismic waves is a subject of considerable interest. Previous studies (Banerji, 1930; Oliver and Ewing, 1957) of microseisms with periods greater than 10 seconds but usually less than 20 seconds showed that such ground motion may be generated by swell of identical periods in the vicinity of the coastline, probably through a mechanism involving the surf. These early studies were confined to waves observed only in the vicinity of the coast, but later studies (Pomeroy, 1959) as well as other unpublished data show that the disturbances may be generated near the coast and propagated inland as Love and Rayleigh waves. In some cases microseismic storms generated by waves striking the east coast of the U. S. were observed as far inland as St. Louis.

The earlier studies cited, as well as the present one, are based on waves of very regular, near-sinusoidal character. Amplitude modulation is in the form of regular beats. The frequency changes very slowly with time, and except for scale, the appearance of the waves is much like that of common 4 to 9 second microseisms. This regular character is of prime importance in identifying the waves. Many long period seismographs record other, less regular, noise in the period range of the present study. In general this noise appears to be related to local effects such as buffeting of the vault or nearby obstacles by winds, man-made disturbances, etc. Some instruments also show occasionally very regular long period disturbances apparently associated with convection cells within the seismometer case (George Sutton, personal communication). After a little experience however, it is easy to distinguish the long period microseisms described here from any of the above types of locally-generated noise.

The results of the earlier studies suggest that the microseisms of the 6 June storm were generated by gravity waves in water incident upon a coastline, and that the dispersion observed in the seismic waves is primarily the result, not of seismic wave propagation, but of gravity wave propagation over an ocean path of some distance. Under this assumption, it is possible to relate the 6 June storm to an unusual meteorological disturbance in the South Atlantic in early June.

An alternative hypothesis attributes the decrease of period with time in the seismic wave train not to propagation in a dispersive medium, but to a complex source related to magmatic activity at the origin of the seismic waves.

In the following, the data on the 6 June storm at a number of stations throughout the world are presented and discussed. A special study of the Palisades data is described and the hypotheses mentioned above are discussed in more detail.

Data and Discussion

A summary of the data used in this study is given in table 1. Table 1 lists all stations with good, long-period seismographs whose records were studied, the range of periods of the waves, the maximum double amplitudes on the records, the time and duration of the storm at each station, the azimuth from the station to the source as determined from the particle motion under the assumption that waves are of the Rayleigh type, and some remarks on the quality of the data.

These stations were selected because they operate seismographs with good long period response. In all cases the seismometers are of either the Columbia or Press-Ewing types, although the operating characteristics vary somewhat from station to station. Most stations arrange the instruments so that the displacement response curve is nearly flat in the period range discussed here and the corresponding gain is usually between about 500 and 2000. Wichita Mountains operates an instrument with a gain of about 10,000 in this period range but the local noise is high and operation was intermittent during June of 1961. Palisades runs a variety of instruments that recorded the long period microseisms, including a three-component set like those described above for most stations. The records of figure 1, on which the data of figure 3 are based, are taken from an instrument whose response curve rises fairly rapidly with period in the range of interest here, with an increase of about 40 per cent between 20 and 30 seconds. The absolute gain in this range is about 8,000 and the instrument is described in Sutton and Oliver (1959) and there designated 30–100 P2.

With the exception of Pietermaritzburg and Honolulu, where storms of microseisms with periods of less than 10 seconds occurred during the time interval of interest and may have obscured waves of longer periods, microseisms with periods of 26 to 27 seconds were observed at all stations listed in table 1. These waves are quite pronounced at some stations, but at others are weak and can only be seen on careful inspection. Identification of the waves at Hong Kong is doubtful because of the high local noise level. The close agreement in period and arrival time of the waves at all other stations is convincing evidence that the observed waves are part of one storm. The data from most stations are summarized in figure 2 where period is plotted as a function of arrival time for each station. Only those points are plotted which correspond to an unbroken wave train of at least 10 cycles, so the error of measurement of period should in most cases be less than about $\pm\frac{1}{2}$ second. A dashed and a solid line are shown with each set of points for comparison. The significance of these lines will be discussed in a later section.

The amplitudes at most of the stations are so small and the masking effect of the shorter period microseisms is so great that no quantitative study of amplitude variation with location or with time can be made. The term "small" is used in the fifth column of table 1 to describe waves whose amplitudes cannot be measured well, either because they are small in themselves or small in relation to the amplitudes of the shorter period background. The amplitude study, as well as the precise determination of azimuth, is also hampered by inexact knowledge of the

TABLE 1

Station	26–27 sec Micro-seisms	Approx. Period Range in Seconds	Approx Time Interval on 6 June 1961 GCT	Approx. Max. Double Amp. of Trace in mm	Azimuth	Remarks
Agra, India	yes	27.5–26.1	1300–1600	small	S	Z and N only
Bermuda	yes	27.4–26.7	1300–1900	small	—	Records good for Z only
Florissant, USA	yes	27.2–?	1330–?	1	E?	Traces overlap-records to 1900 only
Halifax, Canada	yes	27.0–26.0	1300–1900	small	SE	Azimuth determination appears reliable but N & E occasionally shift phase
Hong Kong	yes (?)	—	—	—	NW?	Records noisy, identification uncertain
Honolulu, USA	no	—	—	—	—	Short period microseisms of high amplitudes
Mt. Tsukuba, Japan	yes	27.0–26.0	1400–1900	small	NW	Azimuth good
Ottawa, Canada	yes	26.9–26.7	1200–2000	½	—	Operate Z only
Palisades, USA	yes	27+–26.4	1100–2000	1	ESE	Azimuth good—see special study
Pasadena, USA	yes	27.1–26.0	1200–1900	1+	ESE	N & E sometimes have odd phase relationship, may be ENE
Perth, Australia	—	—	—	—	—	Not in operation
Pietermaritzburg, Union of South Africa	no	—	—	—	—	Short period microseisms of high amplitudes
Resolute, Canada	yes	27.5–25.8	1300–1700	small	(E?)NE	Gain low, waves weak
Rio, Brazil	yes	27.0–26.4	1200–1500	small	E or W	No Z—weak on E, nothing on N
Suva, Fiji	yes	26.7–25(?)	1500–	—	—	Weak on Z, nothing on N or E
Uppsala, Sweden	yes	27.6–26.3	1100–2000	½	SW	Microseisms apparrently larger on E, may be instrumental difficulty
Victoria, Canada	yes	26.8–26.0	1400–1600	small	SW(?)	Weak
Waynesburg, USA	yes	27.0–26.4	1100–2400	1	—	N & E noisy
Wichita Mts., USA	yes	27.6–26.8	1500–2100	6	?	No E, particle motion hard to determine, N(?)

gain of the instruments. The quadrants from which the waves approach can be found however, and in some cases a finer resolution of direction may be obtained. This directional study might be complicated slightly by lateral refraction, but refraction effects should be quite small if, as is likely, the seismic waves traveled in the fundamental Rayleigh mode over both continental and oceanic paths. There is little difference in phase velocities for continental and oceanic paths for Rayleigh

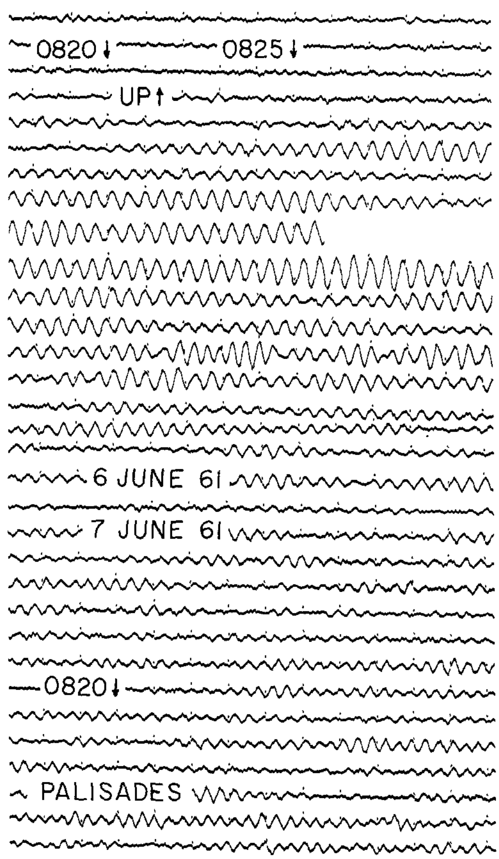

FIG. 1. Seismograms of vertical component 30-100 P2 instrument at Palisades showing sudden beginning, interval of large amplitudes, and low amplitude "tail" of storm.

waves in this period range. Assuming only that the quadrant from which the waves appear to arrive at each station is correct, it is possible to determine a limited area from which the waves must have originated. With the exception of Victoria where the waves are very weak and the determinations of direction questionable, the data from all stations are consistent with origin of Rayleigh waves from an area which includes the Atlantic coastal zones of Africa between about 10°N and 25°S and the adjoining sections of the Atlantic Ocean extending as far as about 25°W and 45°S. This area includes the entire Gulf of Guinea and the Island of Tristan de Cunha.

At Palisades a more complete set of data on variation of the storm with time is available. Palisades data for table 1 are taken from instruments comparable to those of other stations listed in the table. Data from the more sensitive 30–100 P2 instruments are plotted in figure 3 and include an interval of over 2 days. When the storm was observed at other stations, the corresponding waves at Palisades have the same periods and have large amplitudes compared to those of earlier and later times. The Palisades data suggest, however, that the storm began slightly earlier, with waves of slightly longer periods and lower amplitudes than those observed elsewhere, and continued for over two days. During this time interval there is, in general, a regular decrease of period with time to less than 20 seconds. A few points (figure 3) near the end of the interval of high amplitudes fall somewhat

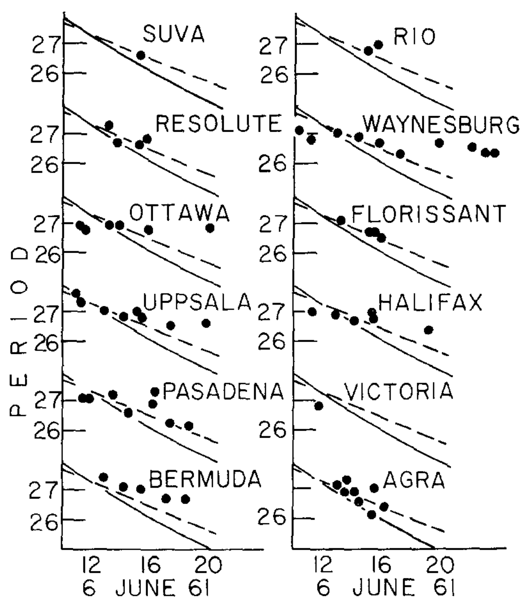

FIG. 2. Circles indicate observed period vs time on 6 June 61 for most stations used in this study. The solid and dashed lines in each section of this figure and in figure 3 may be used for comparison of data from different stations.

above the general trend, and observations at other stations at this time agree with the Palisades data (figure 2). If only the interval of high amplitudes is considered, a smaller rate of decrease of period with time is obtained than if the 2 day interval is considered, but continuity of the Palisades data suggests that the entire two day disturbance is a single event.

The double amplitudes plotted in figure 3 are measured from peak to peak at the point of largest amplitudes within one beat. The data are plotted as taken from the record and correction for the instrument amplification would not affect the general pattern of amplitude versus time which clearly shows the buildup and falloff of the strikingly large amplitudes of the storm during the period when it was detected throughout the world.

Assuming the seismic waves are of the Rayleigh type, a rough calculation of the total energy of the storm during a six hour interval gives about 25×10^{16} ergs and 25×10^{18} ergs for ground amplitudes at Palisades of 0.1 and 1.0 microns respectively.

The larger of these figures is equivalent to the explosive energy in only 600 tons of TNT.

Figure 1 also illustrates the unusual length of the beats during the intense portion of the storm. Although this record was made by a rather sharply-tuned instrument, seismograms from instruments with broader response show the same effect, so it is definitely a characteristic of the earth motion. Following the intense portion of the storm, the beats are generally shorter, suggesting a broader spectrum.

The data indicate that seismic waves, primarily of the Rayleigh type, were generated in, near, or slightly south of the Gulf of Guinea and propagated with amplitudes detectable throughout the world. There is little information from other

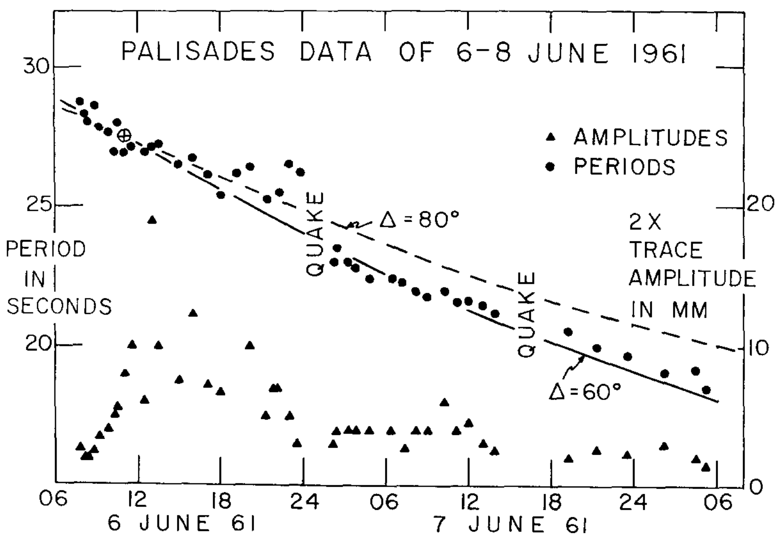

FIG. 3. Circles indicate observed period vs time for Palisades. The solid and dashed lines indicate theoretical arrival times, normalized to the data at a period of 27.5 seconds, for ocean waves from a source at a distance of 60° and 80° respectively. Triangles show amplitudes observed on vertical component seismogram.

types of observations on the possible nature of the source of these seismic waves, but some hypotheses based almost entirely on the seismic data alone may be proposed.

Assuming that the source of the seismic waves consists of ocean waves incident upon the African coast, as suggested by earlier studies, it is possible to account for the observed dispersion as the result of propagation of water waves over a long ocean path prior to the generation of the seismic waves. If the ocean waves are assumed to have been generated by a source very localized in space and time and propagated over a deep water path, the observed dispersion and the arrival times can be used to deduce the time of the source and its distance from the coast. The dashed and the solid lines of figure 3 show theoretical dispersion, normalized to the data at a period of 27.5 seconds (circled cross of figure 3), for distances of 80° and 60° respectively.

A possible source of the water waves, then, is a disturbance at a distance of about

60 to 65 degrees from the north coast of the Gulf of Guinea on about the 2nd of June. No earthquakes or other events, either natural or artificial, which might have generated long-period ocean waves are known to have occurred in the southern Atlantic Ocean at about that time, with the exception of a violent meteorological disturbance at approximately 50° South and 35° West. Such a storm cannot be considered a point source in space or time, but it is possible that the area of generation of the very long waves was limited and the interval during which they were generated was brief. Ocean waves with periods as long as those studied here are unusual and are only generated under extreme conditions.

Weather maps for the Antarctic regions for this time show a deep low pressure center in the region, but data on which the maps are based are very scanty. By coincidence, the Research Vessel VEMA of the Lamont Geological Observatory (LGO) was in the area at the time and accumulated some information on this storm. Figure 4 shows a plot of the meteorological observations taken from the Deck Log of the VEMA for 1 and 2 June 1961. Barometric pressure is given in inches and the arrows indicate wind direction in the conventional sense, i.e., an arrow pointing downward indicates a wind from the north; one to the right, winds from the west, etc. Wind force is measured on the Beaufort scale and descriptions of both wind force and sea state follow approximately the code specified in Hydrographic Office Publication No. 607. From early morning on 2 June to late afternoon of the same date, winds of force 12 (winds of hurricane force and maximum of the scale as used on VEMA) and sea states of 8 (also maximum of the scale as used on VEMA) were observed. During this period the winds at the VEMA were from the WSW or SW direction.

Dr. Maurice Ewing, director of LGO and chief scientist of the VEMA at that time, has had long and varied experience at sea. He stated emphatically that this storm was the most severe he had ever witnessed. The VEMA's Deck Log for 1400 GCT on 2 June 1961 has the following unusual entry: "Tremendous sea tore #1 boat out of chocks and landed it on top of charthouse, smashing it badly." The time of this event is only one hour later than that predicted for the origin of the waves on the point source calculation and the calculated distance is almost exactly the same as the VEMA's distance from the northern coast of the Gulf of Guinea.

The close agreement between the VEMA's data on the storm and the calculations based on the point source approximation is certainly partly fortuitous, but there can be no question that an exceptionally violent storm was in progress at about the time and place suggested by the ocean wave hypothesis. Of course, observed variation of parameters of the storm with time is probably largely due to passage of the storm over the VEMA, and there is no way, unfortunately, to isolate variation of the storm's intensity with time.

The apparent localization of the seismic source near the Gulf of Guinea suggests that either the configuration of the coast is particularly favorable for generation of seismic waves by incident water waves or that the water wave radiation from the storm was very directional, or both. A moving cyclone in the southern hemisphere would radiate waves best to the right of its path, so that a storm traveling westerly or northwesterly would be most efficient in generating waves to the north. A cyclone in this area might move in a westerly direction, but this is contrary to the general trend, and motion in this direction also appears to contradict the VEMA data. While this evidence is not favorable to the hypothesis under discussion, it is not sufficient to invalidate it. Argentine weather maps, which include the area west of the VEMA's location during the storm, indicate that the storm was complicated by a frontal system. The region unfortunately was dark when the Tiros satellite was overhead during early June. Weather maps for the North Atlantic, incidentally, show no unusual features during the interval of interest.

Propagation as ocean waves over a long path could account for the narrow frequency spectrum of the waves during a short interval of time. In fact, the deviation of wave periods near the end of the interval of large amplitudes from the general trend of the data may, to some extent, be a measure of the departure of the storm

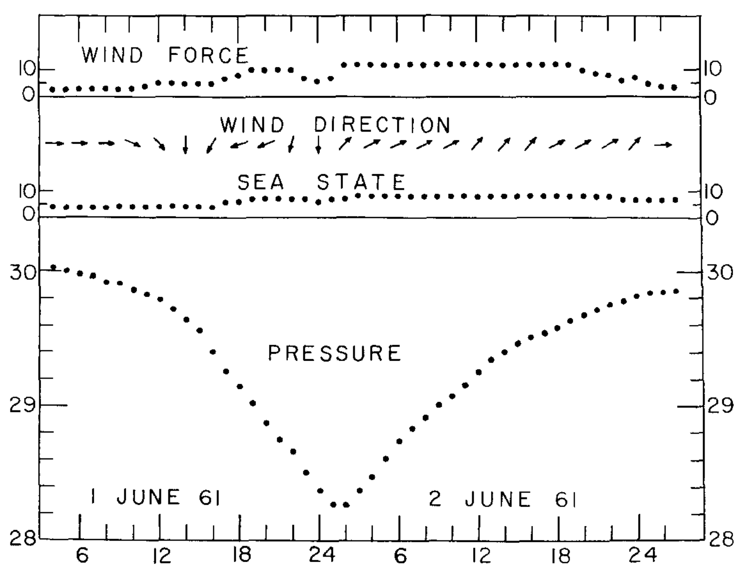

FIG. 4. Meteorological observations from R/V VEMA during South Atlantic storm.

from the assumption of a localized point source. Unfortunately, with the exception of a few shipboard reports of doubtful value, no observations of ocean waves for the South Atlantic could be obtained.

Hydrographic Office Publication #105, *Sailing Directions for the Southwest Coast of Africa*, describes, in the section on Ascension Island, the phenomenon of "rollers" which presents a hazard to ships landing there. These rollers are the near shore effect of ocean swell which apparently has propagated over long distances, arriving from the northeast during the austral summer and from the southwest during the austral winter. The rollers from the southwest are more frequent during the month of June than any other month. The Directions state: "A swell is first observed which, after about 2 hours, reaches dangerous proportions; after about 3 hours, the rollers commence to break and, after about 4 hours, they arrive with their full force. The interval between rollers is about half a minute." These characteristics are in close agreement with those of the 6 June storm and provide support for the ocean wave hypothesis. An early version of the same publication states: "Rollers are experienced along the entire southwestern coast of Africa. . . ."

An alternate hypothesis attributes the character of the seismic waves to a complex source in the Atlantic in or to the south of the Gulf of Guinea. Near-sinusoidal seismic waves are frequently detected in the vicinity of active volcanoes and these are called "harmonic tremor." The waves of harmonic tremors usually have periods of the order of about 1 second or less, but periods as long as about 7 seconds have been observed. It may be that the source of the 6 June storm is of this nature but much larger in scale. There is no direct supporting evidence, such as observed vulcanism, during or shortly after the tremors, as is usually the case with harmonic tremors. Nevertheless, there was an earthquake beneath the Atlantic Ocean at 5.4°S and 11.6°W at $14^h15^m18.9^s$ GCT on 7 June 61, during the second day of the storm, suggesting some tectonic activity in the proper region. Earthquakes in this zone are infrequent. About 4 months later, violent vulcanism on Tristan da Cunha, which is within the possible source area of the seismic waves, forced the

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Mrs. Ruth Simon drew the author's attention to the microseism storm on the Palisades records. Helpful discussions were held with Drs. Maurice Ewing, John Nafe, and George Sutton.

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Note added in proof: After this paper was completed, long period seismograms from Hallet in Antarctica and Santiago, Chile became available. At neither station was the storm clearly evident, but noise level was moderate to high. Drs. Haubrich and Munk of the Scripps Institute of Oceanography kindly analyzed, by a digital technique, a selected section of La Jolla records. They obtained results which agree both in period and azimuth with the pattern described here.

The instruments at Agra were moved to Delhi prior to this storm and the data discussed in the text are from Delhi, India rather than Agra.