MICROSEISMS AND OCEAN STORMS

By Marion H. Gilmore

Foreword, by Frank Neumann

For over a third of a century the relation between microseisms and ocean storms has been the subject of lively but largely academic discussion among seismologists all over the world. Little has been accomplished, however, except to stress the meteorological origin of microseisms. The present paper definitely transfers the subject from the realm of the academic into the category of applied sciences, as it now appears that seismological observations will soon become an essential part of routine weather prediction, especially with reference to hurricanes. In scope and importance this is paralleled only by the successful adaptation of seismological methods to the delineation of subsurface structure a quarter century ago in the quest for oil.

Seismologists have every right to feel gratified over the success achieved in the two seasons of experimental work conducted by the Navy and described in Mr. Gilmore's paper. Many will ask, however, why was this demonstration so long delayed; would not an earlier solution of the microseism problem have been an invaluable aid to the Navy throughout the war; and could not those harrowing experiences in the typhoons off Okinawa in 1945 have been avoided? The answer is a very probable yes. Two factors played an important part in the delay, and it will be well, for the sake of future research in this and related fields, to at least direct attention to them.

First, there has been almost a world-wide and woeful lack of funds to carry on seismological research on the scale required, presumably because seismology has been generally considered an academic subject notwithstanding its successful application to the exploration of subsurface structure. Secondly, the literature reveals so many opposing viewpoints on the cause of microseisms that seismologists as a group did not emphasize sufficiently the primary need for the additional basic data needed to solve their problem. We know now that in a field as undeveloped as seismology any programs aimed at obtaining factual data must be given the right of way over purely theoretical discussion. It was the tripartite station researches of the Rev. J. E. Ramirez, S.J., sponsored by the Rev. Dr. J. B. Macelwane, S.J., of St. Louis University, which broke through the fog of confusion on the cause of microseisms and released new facts which eventually led to the successful microseismic project of the Navy.

Mr. Gilmore points out that the factors which control amplitude are not clearly understood and suggests that the data collected over a long period of years may be needed to clarify the problem. Geophysicists see in this a valuable new tool in the possible delineation of crustal structure in regions of intensive microseismic investigation. Similarly, the differences in the velocity of the waves at the various stations would seem to have special significance. The complexities of crustal structure, both oceanic and continental, may be expected to be revealed in part at least by thorough and systematic study of microseismic data. Geophysicists hope that such research will be conducted as the data are accumulated, or that ways may be found to make the original data available to interested geophysicists.

Assuming that new microseismic stations will eventually be established all over the world by various agencies and governments, seismologists are unanimous in urging that such stations adapt their observational programs also to the recording of earthquakes. Microseismic instruments are earthquake recorders of a very high order, and it would require little more than the addition of good timepieces to fill many glaring voids in the distribution of seismographs over the world, especially in the large oceanic areas. Additional stations are needed to make more accurate earthquake locations and to obtain more nearly complete data on seismic wave speeds needed in studies of the interior structure of the earth. Close coöperation between seismologists, meteorologists, and aerologists would immeasurably advance knowledge in these fields.

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The microseisms discussed in this paper deal with those more or less sinusoidal waves which are frequently recorded on seismographs with periods between two and seven seconds. Some writers are inclined to call them "Rayleigh waves" or "Pseudo-Rayleigh waves." Most seismologists now agree that the ultimate cause of these microseismic waves lies, in some as yet unexplained manner, in the changing meteorological conditions over the face of the earth, especially severe pressure changes. There are two outstanding theories that attempt to explain how it is possible for deep atmospheric lows to cause microseisms.

The oldest theory, suggested by Wiechert[1] in 1904, contends that in Europe they are produced by the pounding of storm-driven surf against the steep coasts of Norway. For many years Gutenberg[2] strongly supported the surf theory, especially as applied to North America, about which he wrote: "The data available indicate that, in the west, the surf produced by storms against the coast of Alaska and northern Canada, occasionally also by cyclones in Mexico, is the cause of the regular microseisms with periods of 4–10 seconds, and that in the east it is the surf driven against the Canadian coasts."[3]

[1] E. Wiechert, "Verhandlungen der zweiten internationalen seismologischen Konferenz, Strassburg, 1903," *Beitr. z. Geophysik*, Erganz.-Bd. 2, pp. 41–43 (1904).

[2] B. Gutenberg, "Die seismische Bodenunruhe," *Beitr. z. Geophysik*, 11:314–353 (1912); "On Microseisms," *Bull. Seism. Soc. Am.*, 26:111–117 (1936).

[3] "On Microseisms," p. 117.

The second theory, suggested by Ramirez,[4] and others, states that microseisms are produced directly by deep atmospheric lows or by strong winds blowing over the oceans and that it is not necessary for heavy storm-driven surf to reach and pound against a steep coast. According to this theory, the vibrations produced by the storm itself are directly transmitted to and through the water to the ocean bottom. From there the generated microseisms are transmitted outward in more or less concentric circles. Lee wrote: "The directions of arrival are inconsistent with the theories that the oscillations are caused by the action of wind or waves on steep coasts, or by the motion of the waves over shallow water. The results set out in the foregoing paragraphs show that the connection between the storms and the microseisms cannot be explained from the current hypotheses."[5]

In the past forty years many excellent papers and books have been written in an attempt to explain more fully these phenomena, and, as a natural result, adherents for either school of thought have been found among the world's outstanding seismologists. Yet, after making a survey of the published papers on microseisms, the author frequently noticed two types of error. Nearly all the papers discuss microseisms and the "directions they are coming from" or "seem to come from." Most of the papers fail, however, to explain satisfactory methods for getting true bearings of the microseismic waves. The second error is that too many writers attempt to show that one cause of microseisms depends upon setting into oscillation a whole continent or more. Recent investigations indicate that one source seldom causes microseisms over an area as large as North America.

Lee discussed the direction of approach of microseisms at some length[6] and described his methods thus: "A method of determining the direction from which the microseismic waves approach an observatory has been developed from a study of the differences between the phases of the horizontal and vertical components of the microseisms."[7] This theory is based on the assumption that all microseisms are true Rayleigh waves, which, from certain pertinent evidence, is doubted by some seismologists. If microseisms are true Rayleigh waves, the direction might easily be determined by Lee's method. Directional results obtained by him, however, were very general. In the light of recent work it seems probable that his inability to obtain more precise bearings may have resulted from the lack or infrequency of pure Rayleigh waves on which to make measurements. It should be pointed out that his results were valuable for being an advance step in the right direction. The question can some day be answered more fully by checking directions obtained

[4] J. E. Ramirez, S.J., "An Experimental Investigation of the Nature and Origin of Microseisms at St. Louis, Missouri," *Bull. Seism. Soc. Am.*, 30:35–84; 139–178 (1940).

[5] A. A. Milne and A. W. Lee, *Earthquakes*, new edition revised by A. W. Lee (1939), p. 210.

[6] In Milne and Lee (as cited) and in his paper, "On the Direction of Approach of Microseismic Waves," *Proc. Roy. Soc. London*, Ser. A, No. 886, pp. 183–199 (1935).

[7] *Earthquakes*, p. 209.

by this method with the directions obtained from the tripartite seismograph stations suggested and used by Shaw, Krug, and Ramirez.[8]

Gutenberg,[9] and a few others, looked for a heavy storm-driven surf pounding against a steep coast a few thousand miles away and attempted to show that it produced microseisms over a whole continent. Results of recent work show that this theory is weak and should be accepted with caution.

Ramirez[10] made accurate measurements on the approach of particular microseismic waves by using three stations close together. The seismometers he used were so located as to form a right-angled triangle: two were placed at the vertex and the other two about six kilometers away on the two legs. He found that any microseismic wave or any particular peak of a wave passing over the tripartite station could be accurately recorded, and the arrival times determined. If the very small differences in times of arrival at the three stations are accurately measured, the absolute direction of propagation of the wave can be calculated, *regardless of whether it is a true Rayleigh wave or the product of some very complicated combination of waves.*

The type of wave motion recorded being still in doubt, no other method is known whereby the direction of propagation of a microseismic wave can be accurately determined. It has been found in normal microseismic waves that the motion of the earth particle is sometimes linear, with frequent variations of directions of motion, and just as often it is either circular or elliptical. It is therefore apparent that the formation of definite opinions and conclusions should not be hastily drawn unless the absolute directions of arrival of the microseisms are known.

It is possibly true that now and then some one source will produce microseisms over a whole continent at one time. However, recent research in the Caribbean indicates that this is a rare exception rather than a general rule. It is believed that many erroneous conclusions have been reached by attempting to find a common source and cause for microseisms recorded at such widely separated seismograph stations as San Juan, Weston, and Berkeley, or at Pasadena, Sitka, and Georgetown. It will be shown later in this paper that certain seismograph stations in the Caribbean area, not more than six hundred miles apart, often do not record microseisms from the same source. Hence it was found necessary to know, without any doubt, the directions from which the microseisms were coming in order to determine accurately their source and cause. Assumptions of directions will not suffice for proof.

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[8] J. J. Shaw, "Communication de M. J. J. Shaw sur les mouvements microseismiques," *Comptes rendus* des Scéances de la Première Conférence réunie à Rome du 2 au 10 mai, 1922, Union Géodesique et Géophysique Internationale, pp. 52–53 (1922); H. D. Krug, "Ausbreitung der natürlichen Bodenunruhe (Mikroseismik) nach Aufzeichnungen mit transportablem Horizontal-Seismographen," *Zeitschr. f. Geophysik*, 13:328–348 (1937); J. E. Ramirez, S.J., "An Experimental Investigation" (see note 4, above).

[9] "On Microseisms" (see note 2, above).

[10] *Op. cit.*

With a view to investigating the possibility of using microseisms to detect and track hurricanes, the Joint Meteorological Committee of the Joint Chiefs of Staff of the Army and Navy, and the Chief of the Weather Bureau, in 1943, proposed a detailed study of the entire history of microseisms and obtained the opinions of leading seismologists in this country concerning the proposal. In spite of the fact that some seismologists advised against the contemplated study, the Joint Committee finally decided to recommend that additional research be undertaken. Upon the Committee's recommendation, the Navy Aerological Service initiated a comprehensive research project to record and study microseisms in the Caribbean. The writer was directed, late in 1943, to assume active charge of field operations of the newly formed Hurricane Microseismic Research Project, and since that time has actively supervised all phases of the research program. For the year 1944 the Rev. James B. Macelwane, S.J., was retained by the Navy as a technical consultant, and did much to make the project a success. The officers and technicians of the United States Coast and Geodetic Survey and the Weather Bureau freely gave their time, offered advice, and coöperated with the officer in charge on all phases of the project. The author is appreciative of this unselfish coöperation which contributed in a large measure to the success of the project.

In August, 1945, Dr. Beno Gutenberg, of the California Institute of Technology, was retained as a technical consultant. After reviewing the results already obtained and after making a special investigation (by air) of surf conditions in certain areas of the West Indies, he made the following statement in the first Navy press release, dated November 15: "The studies which I have made here thus far leave no doubt that the data from microseisms furnish valuable information for the forecasting of hurricanes. The correlation between the microseisms and storms is convincing." At present, it is the author's belief that although some microseisms may be caused by surf, they are secondary as compared with those caused by deep lows over the ocean, and play no part in tracking hurricanes by measuring the directions of the dominant microseismic waves.

The first completely equipped tripartite seismograph station was established at the Naval Operating Base, Guantanamo Bay, Cuba, in September, 1944, in accordance with the method outlined by Ramirez[11] six years before. As the project developed, major improvements in technique of operation and in design of instruments were made, in order to meet the needs of actual field practice. Nevertheless, the basic principles of using a tripartite station as stated by Ramirez and Macelwane were retained.

Ramirez used four seismometers as described in his paper.[12] Present practice requires only three seismometers, one in each of three vaults at the vertices of a triangle as shown in figure 1. They record the arrival times of the microseismic

[11] *Op. cit.* [12] *Op. cit.*

waves so that a mathematical solution will give the direction of propagation. The times of arrival of a particular wave at the three stations is determined by the use of simultaneous time marks on all three records. The records are obtained at a central station using a triple-drum recorder. *Regardless of the*

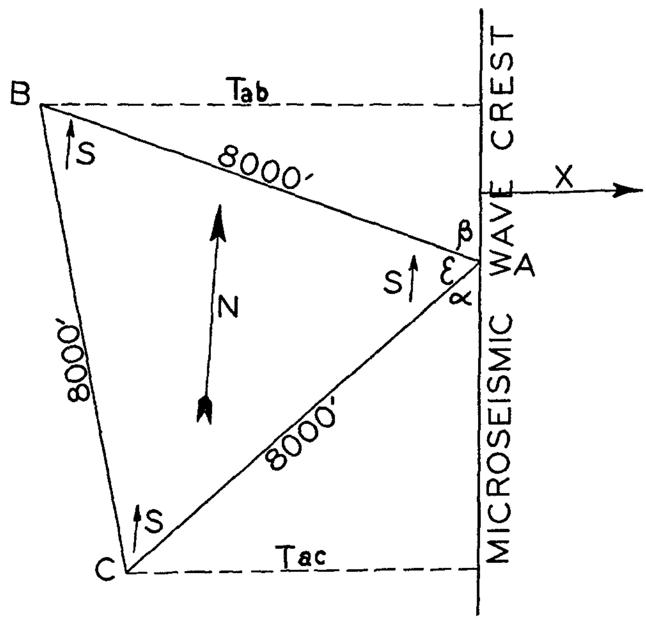

Fig. 1. Diagram of tripartite seismograph station and microseismic wave crest.

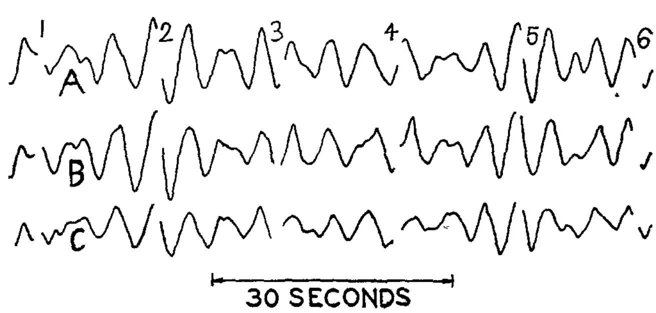

Fig. 2. Records from three seismographs at Richmond, Florida.

type of wave being recorded by the three seismometers, all possible directions of propagation will produce corresponding differentials in times of arrival at the three stations. From these time differences the *direction* in which the microseismic wave is traveling *can always be calculated.*

Figure 1 shows a typical station as now used in hurricane research throughout the Caribbean, Gulf, and Pacific. Each side of the triangle is approximately eight thousand feet in length, and it is believed that this short distance will be reduced materially as a result of experiments now in progress. As soon as the first bearing is determined, the three instruments at each station are rotated in such a way as to record the component in the direction from which the waves arrive. The component perpendicular to this could be used, although its amplitude would be somewhat smaller. Figure 2 shows actual parts of records from the three seismometers at the Naval Air Station at Richmond, Florida.

As previously indicated, the first step in the actual calculation of a bearing is to measure the differences in times of arrival between the stations A and B, A and C, and B and C. The linear distances (as shown in Table 1) from the crests of certain well-formed microseisms recorded at *all three stations* are measured in millimeters to the nearest time break. Since linear distances and time differences were strictly proportional over the small distances of a tripartite station, it was unnecessary to convert the values to actual travel time. The data from figure 2 have been measured, and are shown in table 1.

TABLE 1
LINEAR DISTANCES BETWEEN STATIONS A, B, AND C

Station	1	2	3	4	5	6	Average
A–B	1 10	1 10	0 90	1.00	0 80	1.00	0 983 mm.
A–C	0.80	0.70	0.80	0.80	0.70	0.90	0.783 mm.
B–C	0.30	0.30	0.10	0.10	0.20	0.20	0 200 mm.

The general formula derived for the determination of direction of arrival of microseisms at a tripartite seismograph station is similar, in parts, to those developed by Ramirez[13] and Krug.[14]

1. In figure 1, let $L - L_1$ be any microseismic wave peak (in this case) striking station A first, making angle α with side AC, and angle β with side AB.
2. Let angle ϵ be less than 180°, and the sum of $\alpha + \beta + \epsilon = 180°$.
3. Let V be the average velocity of the microseismic wave peak over the station.
4. Let T_{ac} be the difference in travel time from station A to station C, and let T_{ab} be the difference in travel time between stations A and B.
5. Then: $\sin\alpha = VT_{ac}/b$, and $\sin\beta = VT_{ab}/c$

   or $$\sin\beta = \left(\frac{bT_{ab}}{cT_{ac}}\right)\sin\alpha = K\sin\alpha, \text{ where } K = \frac{bT_{ab}}{cT_{ac}}.$$
6. $\text{Sin}\,\beta = \sin[\pi - (\alpha + \epsilon)] = \sin(\alpha + \epsilon)$

   or

   $\sin\beta = \sin\alpha\cos\epsilon + \cos\alpha\sin\epsilon = K\sin\alpha.$

[13] *Op. cit.* [14] *Op. cit.*

7. $\sin \alpha(K - \cos \epsilon)/\cos \alpha = \sin \epsilon$.
8. Therefore: $\tan \alpha = \sin \epsilon/(K - \cos \epsilon)$.

Using the data obtained in table 1 and figure 1,

$$\text{Let } K = \frac{0.983 \times 8000}{0.783 \times 8000}; \quad \sin \epsilon = \sin 60°; \cos \epsilon = \cos 60°.$$

Substituting these values in the formula given above,

$$\tan \alpha = \frac{0.866}{\dfrac{0.983 \times 8000}{0.783 \times 8000} - 0.500} = 1.146.$$

$$\alpha = 49°.$$

The slope of side AC clockwise from true north is 225°. The direction of propagation of the microseismic wave, x, is given by the equation $x = 225° - (\alpha + 90°)$. In the case above, $x = 86°$.

The direction of arrival of microseismic waves at a tripartite seismograph station can always be determined either by the formula given above or by constructing travel-time curves. The average velocity of the waves cancels out of the equations for direction calculation, and must be determined directly. Therefore, when sufficient data have been collected at one station it is possible to draw the travel-time curves similar to those shown in figure 14. From these curves directions can always be speedily determined as soon as the differences in times of arrival have been measured from the records. It is often advisable to check one method against the other in order to obtain a higher degree of accuracy. All directions obtained in this research were by calculation, and the travel times measured were used to construct travel-time curves for each tripartite station, similar to those shown in figure 14.

Early in the hurricane season of 1944 a single-component station was established at the Naval Operating Base, Guantanamo Bay, Cuba. The first hurricane passed about one hundred miles south of the station. Unfortunately only one of the three instruments had been installed at that time. The storm did not develop into a major hurricane, but was apparently the cause of very large microseismic activity. The Coast and Geodetic Survey seismograph station at San Juan recorded a large increase in microseisms as the storm passed to the south of the island of Puerto Rico. Twenty-four hours later the storm was south of the Cuba station, where the microseisms increased from a low of 3 mm. to a high of 55 mm. The microseismic activity gradually built up to a maximum, which was reached when the storm was in the region of its nearest approach to this station. Two days later the activity was again normal and the storm had advanced to the Gulf of Mexico, as shown in figure 3. It is reasonable to conclude that this storm had some important connection with the very large increase in microseismic activity at the two stations; but there is no way to prove this conclusion, because at that time neither station was equipped to secure directional data.

The Guantanamo Bay station was soon completed as a tripartite seismo-

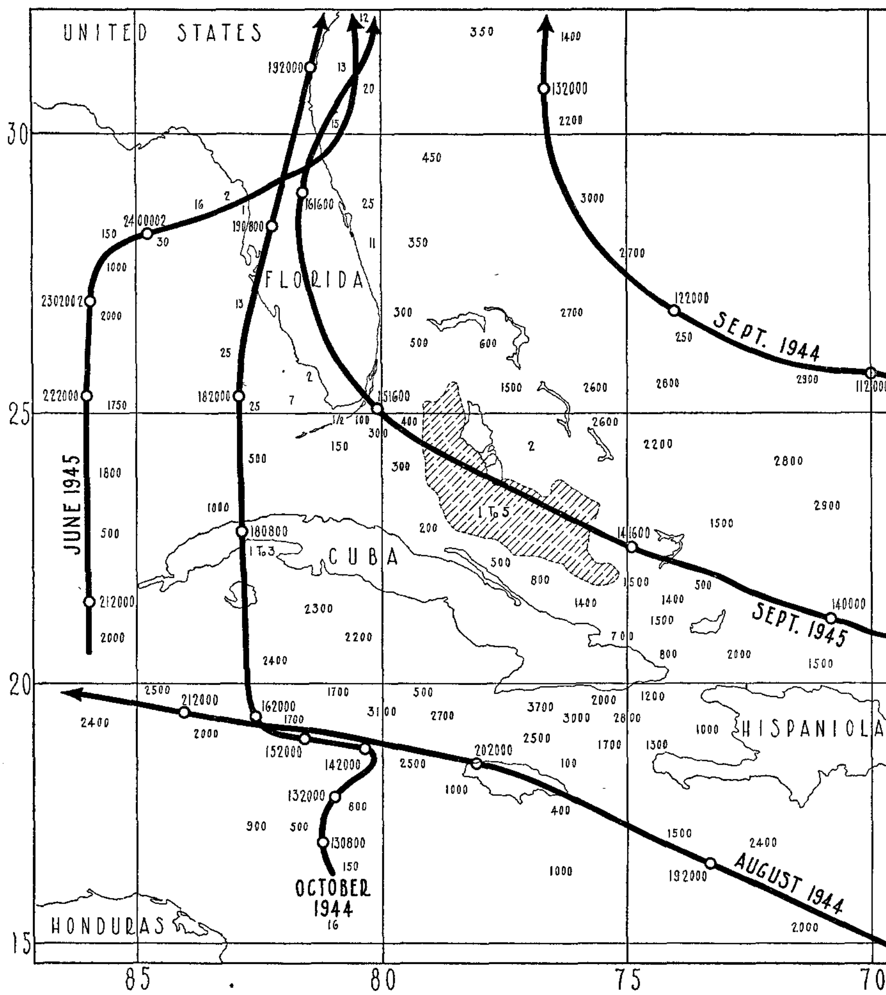

Fig. 3. Storm tracks in the Caribbean for 1944 and 1945.

graph station from which accurate bearings were obtained on both tropical and extratropical storms. The track of the second hurricane of the season is shown in figure 4. It also shows the double trace amplitudes of the microseisms and the directions obtained. The amplitudes indicated on this and all other charts in this paper are plotted to the scale shown on the left margin. One millimeter double trace amplitude equals an approximate displacement of the earth particle of 0.00250 millimeter when the average period is about 6 seconds. The time and date are shown at the bottom of the maps and charts in terms of Greenwich Civil Time throughout, unless otherwise stated.

The hurricane shown in figure 4 developed near Martinique and passed

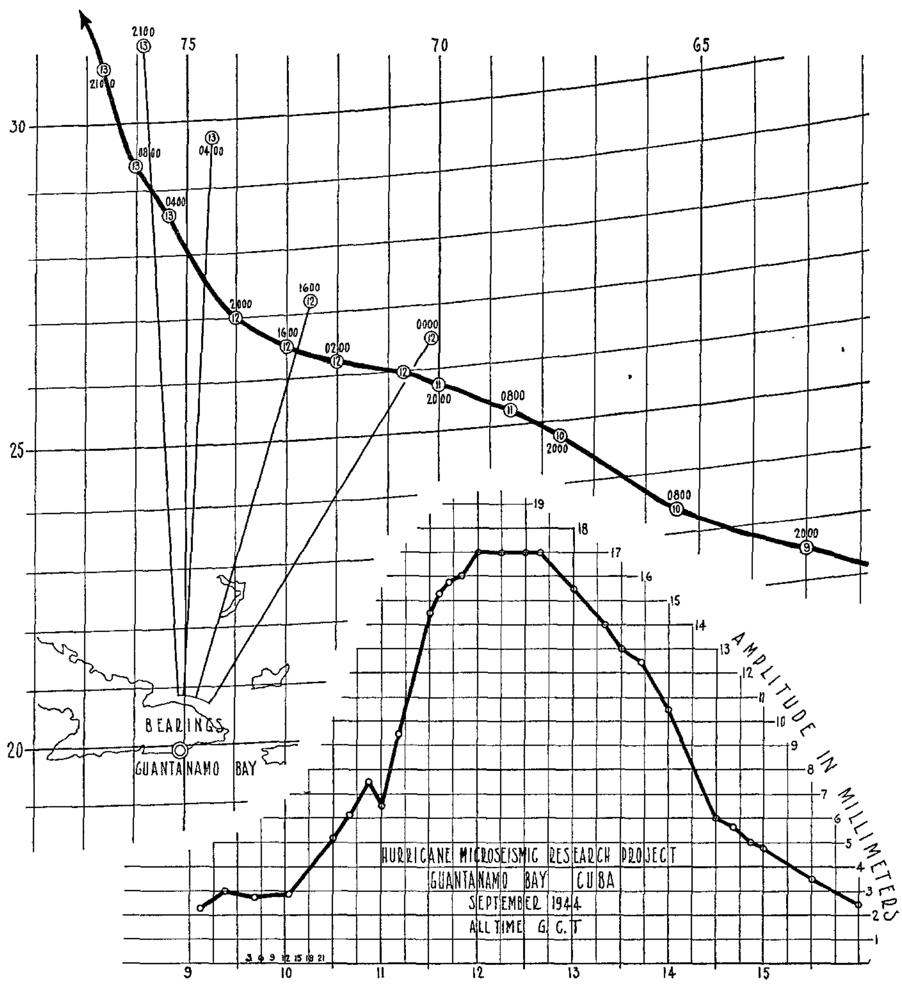

Fig. 4. Hurricane track and amplitude chart, September, 1944.

north of Puerto Rico, Haiti, and eastern Cuba, and then curved sharply northward. The microseismic amplitude increased from 2 to 19 mm. in four days. After reaching a peak the microseisms gradually decreased and were again normal when the storm passed the New York area. A careful study of figure 4 will show the degree of accuracy obtained in these first measurements, and that the results were similar to those obtained at St. Louis in 1938.

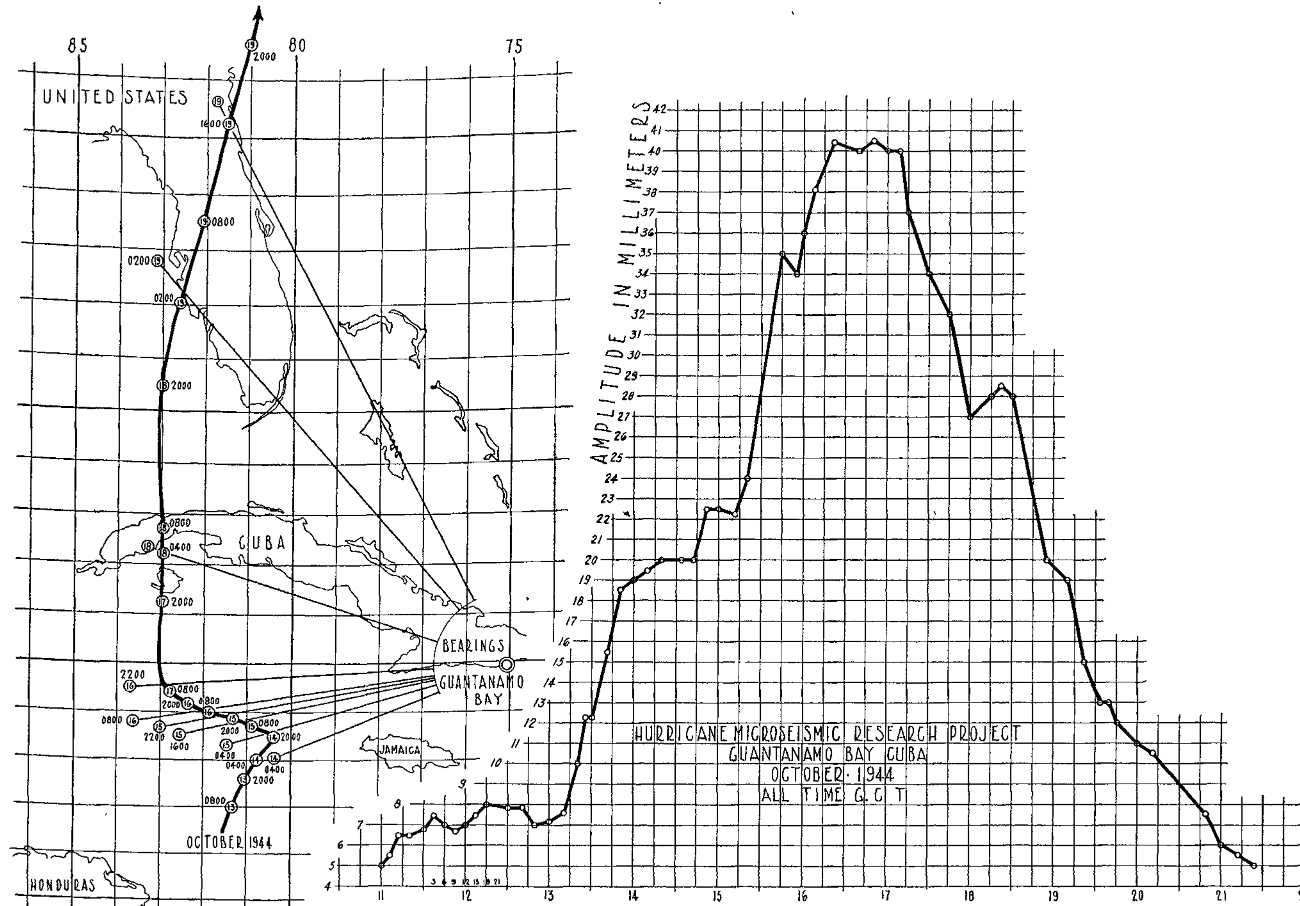

Fig. 5. Hurricane track and amplitude chart, October, 1944.

The third hurricane was detected and located by directions, through data obtained on the Guantanamo Bay seismograph, fully two days before it was officially announced by the United States Weather Bureau and the Navy. The track of this storm is shown in figure 5, together with several bearings. The microseisms increased from 3 to 8 mm. on October 11, and a bearing im-

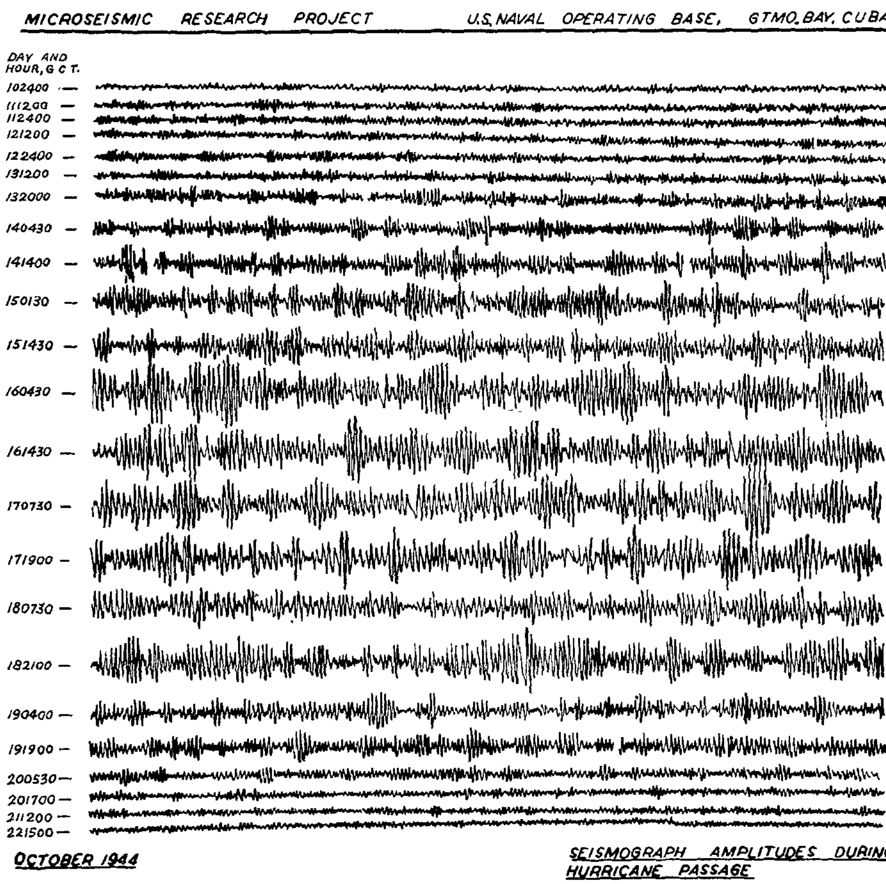

Fig. 6. Tracing of microseisms, hurricane of October, 1944.

mediately calculated pointed directly south. During the next two days the amplitude remained about the same but the bearings gradually shifted to the southwest. The direction from which the microseisms were arriving at Guantanamo Bay was confirmed on October 13 when a hurricane center was found by the Weather Bureau and the Navy.

By October 16 the microseisms had increased to a maximum of 55 mm. as the storm, which was moving very slowly, developed into a disastrous tropical disturbance. It began moving northward over Cuba and up the west coast of Florida with continued high microseismic activity as shown in figure 6. This unique tracing clearly shows how the normal microseisms increased and decreased over a period of eleven days during passage of the storm. Each line represents fifteen minutes of the actual seismograph record obtained at Guantanamo Bay. The traces shown were made at approximately twelve-hour intervals. During the time that the storm was south of Cuba, over Cuba, and passing up the west coast of Florida, the amplitude was very high. During these days the calculated bearings were pointing directly into the storm area as it moved along, and continued to do so until the storm crossed Florida and entered the Atlantic near Jacksonville.

The 1944 data, showing apparent influence of storms by the increase and decrease of microseismic activity, leads to only one possible conclusion, namely, that atmospheric disturbances can be *detected, located, and tracked* with the seismograph. The first season's research confirmed many of the facts and hypotheses submitted by Ramirez, Krug, Trommsdorff, and Shaw. The seismograph was thus found to be a very useful tool for forecasting and tracking severe storms in the Gulf of Mexico and the Caribbean.

These data were presented to a large gathering of officers from the United States Navy and the Coast and Geodetic Survey in December, 1944. All phases of the subject were discussed and it was generally agreed that the findings were conclusive and highly valuable. The Naval Aerological Service not only approved a continuance of the research work, but saw sufficient merit therein to authorize the establishment of two additional tripartite seismograph stations in the Caribbean. It was self-evident that bearings from only one tripartite seismograph station would not suffice to obtain a definite position on a storm. It was considered that bearings obtained from two or more stations, as indicated by data obtained in 1944, should intersect at some point that would be reasonably near the center of the atmospheric disturbance, be it a hurricane, a typhoon, or an extratropical low. One of the new stations was established at the Naval Station, Roosevelt Roads, Puerto Rico, and the other at the Naval Air Station, Richmond, Florida. During the first part of the hurricane season of 1945 the two new stations had only a single-component seismometer each and therefore could not give sufficient data for bearings to be calculated. Nevertheless, extremely valuable information was obtained from them during this time, especially from the station at Richmond.

Early in the season several naval officers and enlisted men were given special training in seismology and in its relation to detecting hurricanes. These men proved adaptable to the work and greatly aided in the research during the second season. With their help and coöperation many new ideas based upon knowledge gained in 1944 were put into actual practice. The biggest improvement was central recording. In 1944, recording was done in three separate vaults, and simultaneous time marks were placed on each record from a master clock over regular telephone wire. In 1945, special lead-shielded cable was connected to each station so that the small current generated by the seismometer coil oscillating between two strong Alnico magnets passed over it and recorded through a galvanometer on a centrally located triple-drum recorder. This proved very satisfactory and a great timesaver. The three stations

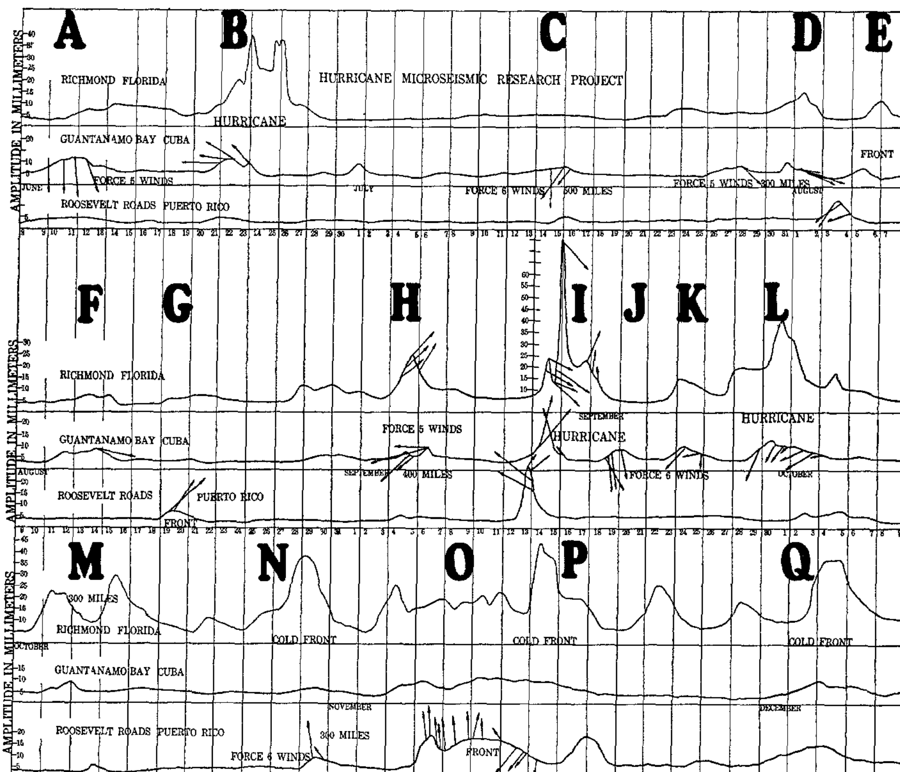

Fig. 7. Amplitude and bearing from all these seismograph stations for 1945.

were arranged in an equilateral triangle (fig. 1), instead of the right-angled triangle used by Ramirez. The new tripartite seismograph station needs only three seismometers, all oriented in the same direction. The distance between the stations forming a tripartite network has been materially reduced, sometimes more than half the former distance. Experiments now in progress indicate the possibility of using distances as short as one mile or even less. In addition, many new features were incorporated in the design of the seismometers and recorders in order to make them more suitable for this type of recording.

The amplitude charts, periods, and phase relationships of the microseisms at the different stations show many important data in connection with velocity and type of wave motion recorded during 1945. Because the station at Guantanamo Bay was installed one year earlier than the other two, it is natural that more data have become available there. The average velocity determined for that station was 2.6 km/sec. for microseismic waves that pass by the three seismographs. The station was established on a coral ledge twenty

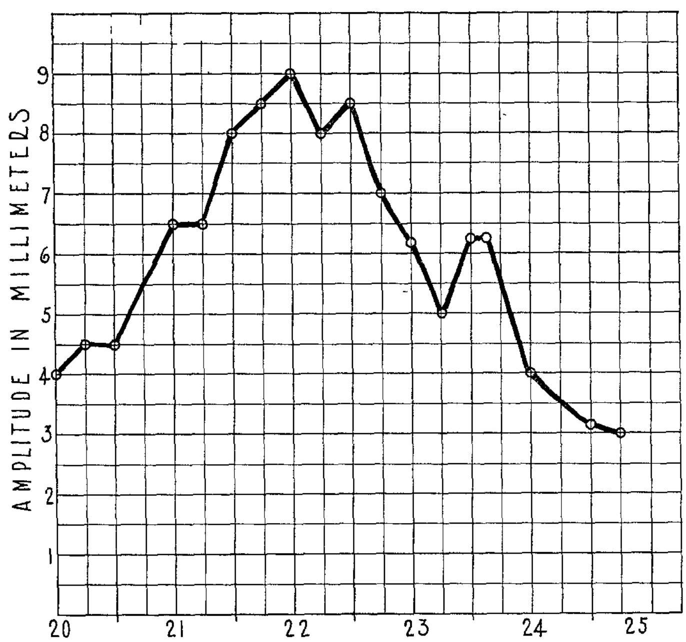

Fig. 8. Amplitude of microseisms from Guantanamo Bay seismograph, June, 1945.

to thirty feet thick which, in turn, rests upon a great thickness of partially consolidated marine sediments. Guantanamo Bay seismometers are fairly sensitive to most types of meteorological lows passing over or near the station, especially anything forming to the south or southwest.

Insufficient data at the other stations will permit only very rough estimates of velocity. The excellent solid rock foundation at Roosevelt Roads is conducive to a high velocity, but the indicated 4 km/sec. seems rather high. The station at Richmond, which is on a thin, partially decomposed, coral rock, appears to have a velocity near 3.25 km/sec., which also seems very high. The Richmond station is the most sensitive of the three. Force five winds or higher around the southern half of Florida will produce microseisms with a double trace amplitude of nearly two centimeters. A cold front passing this station will show very large amplitudes about eight to twelve hours before it reaches the station, see figure 13. From the very even amplitude curve of microseisms shown in figure 7, for Roosevelt Roads, it appears that that station requires a hurricane or a pronounced meteorological front for large microseisms to be recorded. Regardless of the merits of these stations in picking up fronts and

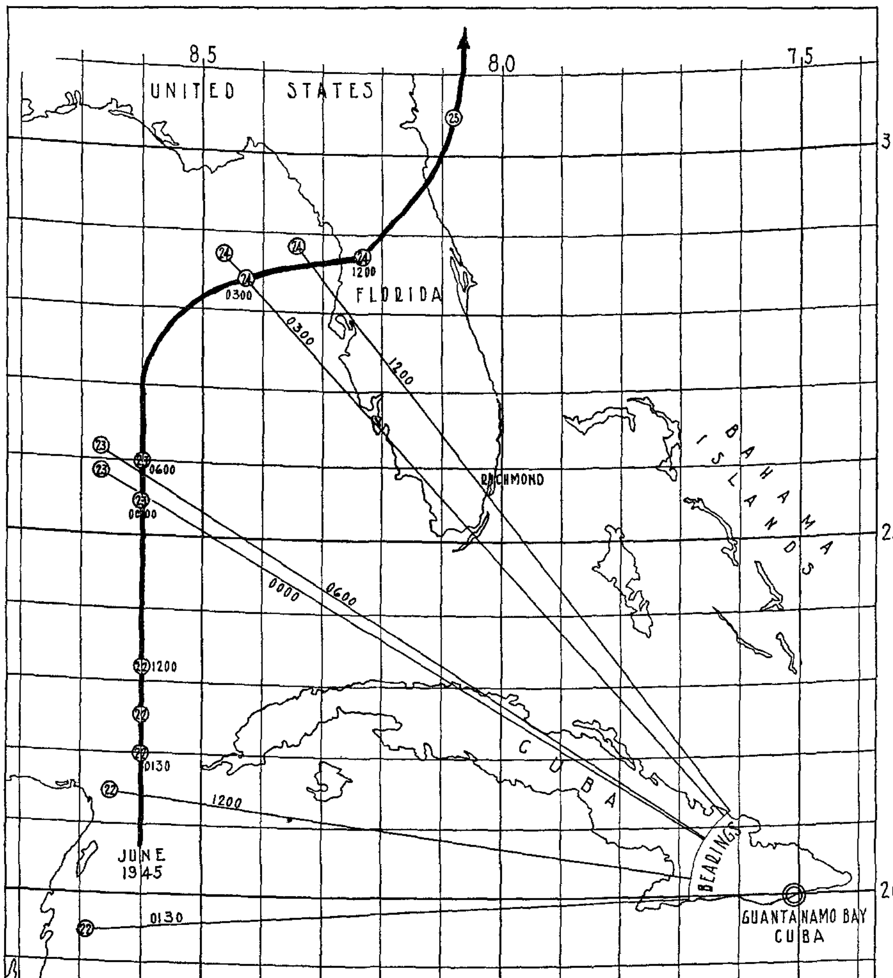

Fig. 9. Hurricane track and bearings from Guantanamo Bay, Cuba, June, 1945.

areas of strong winds, they all detect hurricanes and give good directional bearings on the storm area. It is nearly always possible to analyze microseisms and to tell which are produced by a hurricane and which by strong winds, or possibly by surf around the Florida Keys. This particular phase of analysis can be improved by training and by studying microseisms at a particular station for some time.

The seismograph at Guantanamo Bay reported a slight increase in the amplitude of microseisms on June 21, 1945, with bearings pointing almost due west, as shown in figures 8 and 9. The bearings shifted slowly to the northwest and always, after the first two, pointed directly into the disturbed area of the hurricane. This tropical disturbance proved to be the first major hurricane of the year, and rapidly developed winds of 55 knots. The Navy and Army reconnaissance planes scouted the area during daylight hours and reported the storm moving due north from the western end of Cuba, as shown in figure 9. In spite of the small amplitudes of the microseisms at Guantanamo Bay the bearings obtained were very accurate.

The microseisms recorded at the Richmond station increased about the same time as the Guantanamo Bay station. Figure 10 shows the story of this first hurricane of 1945 as told by the seismograph. The microseisms at Richmond gradually increased to a maximum of 17 mm. when the storm was passing 150 miles west of the station, then began to decrease slowly and in nine hours had reached a low of 14 mm. The microseisms slowly increased again to 17 mm. during the following nine hours and at a time when the storm *was moving away from the station.* Both the Army and the Navy planes continued to report the storm moving northward and with no indication of intensification.

On Saturday morning, June 23, 1945, the Army reconnaissance plane left early and before noon reported the storm with maximum winds still 55 knots, but that it was veering slightly to the west. The Navy scout plane departed for the hurricane area in the early afternoon and its report coincided with that of the Army's morning flight, stating that the storm center had shifted still more to the west. The early afternoon weather maps gave the storm's position a full degree west of its previously reported position, and forecast a continued movement to the northwest, with no indication of increased intensity. Figure 10 shows that the microseismic activity at Richmond increased slightly that day when it normally would have been expected to decrease because the storm was reported to be moving farther away from the station. In mid-afternoon the Army sent another plane to make a last check of the day on the storm's position and intensity. Just before sundown the pilot reported that he had encountered the storm more than one hundred miles east of its supposed position and that in going through its center he had found winds of 85 knots. It can be reasonably assumed that the storm started veering to the east Saturday morning as shown in figure 9, and not as reported. It is also reasonable to suppose that the storm was gradually intensifying at the time the microseisms were slowly increasing. There was, about 5 P.M. (EWT), a very sudden increase in the storm's intensity as it moved northeast. Figure 10 shows that the microseismic activity at Richmond suddenly doubled in amplitude. This fact was reported to all forecasting agencies in Miami soon after 5 o'clock (EWT) and *before* the scouting plane reported the increased intensity of the storm. The forecasting agencies in the Miami area considered the data supplied by the seismograph very valuable and used similar data from other stations throughout the remainder of the hurricane season.

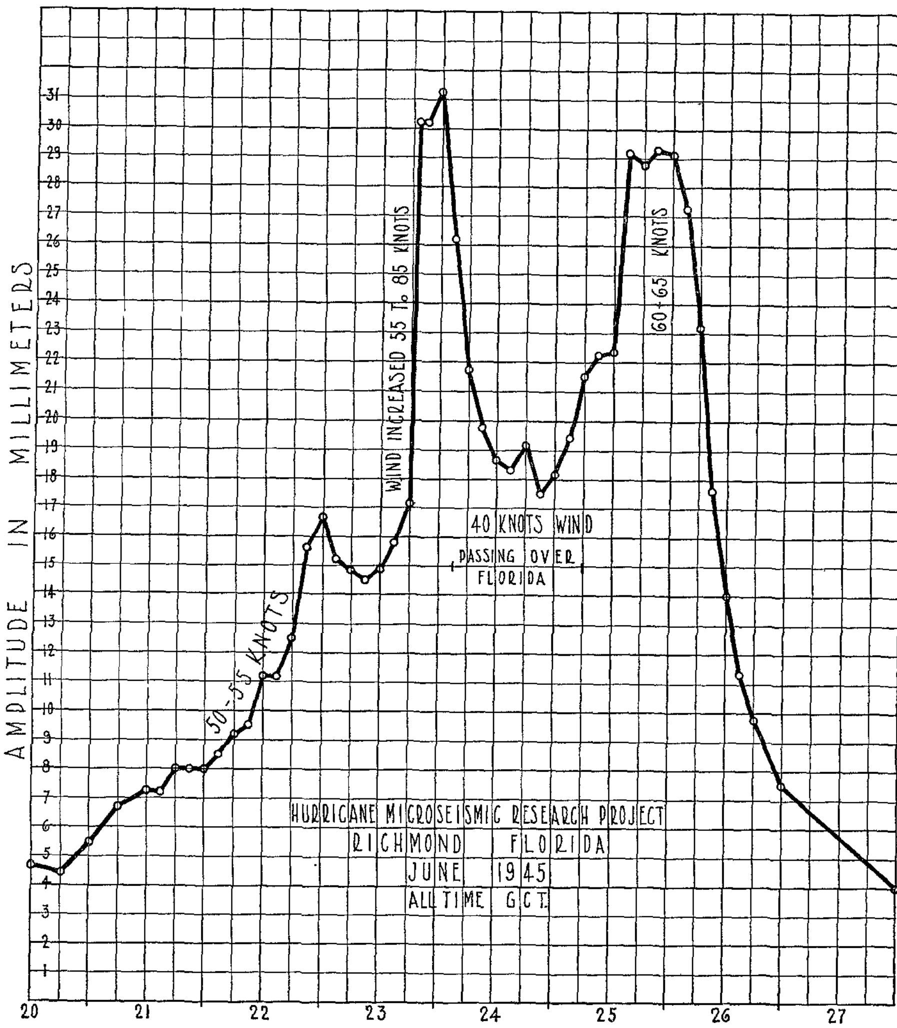

Fig. 10. Amplitude of microseisms recorded at Richmond, Florida, June, 1945.

This particular example of the June hurricane demonstrates an interesting fact concerning the source of microseisms. The waves of the sea travel at various velocities, with a rather well-defined relationship to period. This is shown in the general formula given by Marmer in his book *The Sea*[15] (see p. 184

[15] New York: D. Appleton & Co., 1930.

and the formula $p = l/w$, where p is period in seconds, l is wave length in feet, and w is velocity in feet per second). Seismic sea waves generally have very long periods of 30 minutes or more and their velocities average 400 miles per hour. On the other hand, observed periods of ordinary sea waves caused by hurricane winds average about 10 seconds with wave length of 500 to 700 feet. The velocity seldom gets as high as 30 miles per hour. At this maximum velocity for hurricane sea waves it would have taken a storm wave from the greatly intensified June hurricane six hours to reach and start pounding against the none too steep Florida coast and be transmitted through the ground to the seismograph at Richmond. However, this delay did not occur; in fact, the microseisms recorded by the seismograph doubled in value almost immediately after the storm intensified. At 2 P.M. (EWT), the seismograph amplitude was 17 mm., and in the following three hours it increased to 30 mm. The wind velocity increased from 55 to 85 knots in the same three-hour period. The microseismic impulses generated by the intensified storm traveled to the seismograph in less time than would have been required if they had been transmitted by the increased storm waves to the coast and then through the ground to the seismograph. The sudden intensification of the storm and the rapid increase in the microseismic wave amplitude recorded at Richmond appear to have been almost simultaneous, dependent only on the probable normal travel time for the microseisms between the storm center and the seismograph station. This fact, and the many accurate bearings during this and other storms, leads to a more probable theory than that of surf pounding against a steep coast to explain the cause and source of the large, regular, and dominant microseisms recorded during a hurricane. It suggests that the microseisms are produced by some force within the hurricane itself and that they are then transmitted to the ocean bottom and thence through the ground to the seismograph. Although the above-stated results do not disprove that microseisms are caused by surf, as is held by some seismologists, they indicate quite definitely that such microseisms, if they exist, *could not be used in locating storm centers.*

A study of figure 10 shows that the microseismic activity at Richmond decreased from 32 mm. to 20 mm. as the storm passed over Florida and as the storm's intensity dropped from 85 to 40 knots. However, as the storm passed into the Atlantic the winds increased to 60 knots and the microseisms to 30 mm. There was a large amount of microseismic activity during the time this storm was passing over Florida which might or might not be due directly to the storm's central area.

Again, during a later storm (September, 1945), there was large microseismic activity at Richmond as the storm passed over Florida. It is possible that in both storms the microseisms were due to force five or six winds over southern Florida. It has been observed that stronger winds over the Guantanamo Bay station apparently had no effect on the microseismic amplitude. When a tropical storm reaches land it always decreases in intensity very rapidly and the microseisms also decrease in amplitude. The data at hand are insufficient to warrant a definite statement on the cause of the microseismic decrease. Is it because the storm actually produces no microseisms when it is over land, or because the storm has decreased greatly in intensity, or partly to each cause? Good arguments may be found in support of either theory.

In figure 7 are many new data which give an idea of the microseismic picture as recorded at the three tripartite seismograph stations in the Caribbean in 1945. The major hurricanes are discussed in more detail elsewhere in this paper, and there are also many illustrations showing their tracks drawn to larger scales. The most significant features in figure 7 are marked with large letters from A to Q, and each will be discussed below. Special attention is directed to the hurricanes listed as B, E, and I. All the storms moved from east to west and naturally registered on the Roosevelt Roads seismographs first. As they moved westward they were recorded at Guantanamo Bay, and finally at Richmond. The storms showed almost a twenty-four-hour lag in the appearance of maximum microseismic activity at the three tripartite seismograph stations, which represented an average speed for the movement of the storms.

A. At Guantanamo Bay the amplitude increased from 4 to 10 mm. and the calculated bearings pointed to a disturbed area of force six winds about 400 miles south. Aircraft reconnaissance was used to obtain the facts of strong winds, disturbed areas, and hurricanes each time the microseismic amplitude was large enough for bearings to be calculated.

B. The June hurricane has been discussed above.

C. A very small increase in amplitude was recorded at Guantanamo Bay and force six winds were found south and southeast of the station.

D. The stations at both Guantanamo Bay and Richmond recorded larger than normal microseisms for several days. Bearings from Guantanamo Bay were southeast, away from Richmond and toward Roosevelt Roads. Therefore it is reasonable to conclude that the Guantanamo Bay and Richmond seismographs were recording microseisms from different sources. If it had been the same major source southeast of Guantanamo Bay that caused large microseisms at Richmond, then it is more than reasonable that the nearer station at Roosevelt Roads would have recorded large microseisms. But it did not. Figure 7 shows the amplitude curve at Roosevelt Roads to be almost a straight line for June and July. The disturbed area southeast of Guantanamo Bay contained force six winds and that place was carefully watched by aircraft for several days.

E. This small disturbance developed southeast of Puerto Rico and traveled directly toward Haiti, where it finally broke up and dissipated over the high mountains. It caused the first increase in microseisms at the new Roosevelt Roads station, and several excellent bearings were obtained as it passed south of Puerto Rico. After the central storm dissipated, a frontal wave was carried forward and recorded on the other two stations at about the proper time lag of twenty-four hours.

F. One easterly bearing was obtained on this slight microseismic increase at Guantanamo Bay, which indicated a small disturbed area.

G. A near-development of another tropical disturbance northeast of Roosevelt Roads was indicated by this microseismic increase. Aircraft reconnaissance found a small circulation forming about two hundred miles northeast of Puerto Rico, but after two days the disturbed area passed on northwest and out of range of the stations. It did not intensify.

H. The seismographs at Richmond and Guantanamo Bay recorded large microseisms on which good bearings were obtained. Attention is directed to the direction at each station: Richmond, northeast; Guantanamo Bay, southwest. These stations are only 600 miles apart and were actually recording microseisms from different sources. The Guantanamo Bay seismograph often recorded microseisms of 7 to 10 mm. when the stations on either side showed no increase in amplitude. This indicates that microseisms are often caused by something quite local and that the cause is seldom sufficient to set a whole continent in oscillation.

I. The September hurricane is discussed below.

J–K. After the destructive hurricane in September there were two mild attempts by nature to repeat, as shown in these two increased microseismic peaks. The directions definitely pointed toward much disturbed areas south and southeast of Guantanamo Bay. However, neither developed into a storm and the microseisms soon returned to normal.

L. Even though the October hurricane is discussed below, it is necessary to mention the large microseisms recorded at Richmond. It was ascertained that the large microseisms recorded at Guantanamo Bay were coming directly from the storm area, while those from the Richmond station were believed to be coming from some other source. At the Richmond station, ground water entered the vaults after the September hurricane, and the excessive humidity caused several instrumental failures, thus preventing the calculation of bearings until December. It was observed that force five or six winds around southern Florida or the passing of a cold front very often caused large microseisms of the order of 20 mm. at Richmond. When the June hurricane was south of the west end of Cuba it did not produce microseisms at Richmond. The October storm was even a greater distance south of that position.

M. The Richmond station showed a large increase in microseismic activity for a week, with two distinct peaks. It was impossible to locate accurately the source of these microseisms, because of the instrumental trouble mentioned above, but it is believed that they were produced by two cold fronts passing over the state that week. Peaks similar to these always appeared on this seismograph during the passing of a cold front and other meteorological fronts. Force five winds always produced large microseisms at Richmond, but the character of the microseisms was always very different from those produced by a hurricane. (See figures 6 and 13.) Figure 6 shows regular and dominant microseisms with periods of the order of five to six seconds, whereas figure 13 shows very irregular and short-period microseisms. It has been observed that this relationship always holds true and that microseisms produced by a hurricane can be distinguished from those produced from other causes. The microseisms shown in figure 13 might possibly be produced by force five winds or higher over the Florida Keys, or by a slight surf produced on the very flat coastal plain, or by a combination of both. They are definitely not associated with hurricane development and with careful study can always be distinguished.

N. Richmond again recorded microseisms of more than 25 mm. and again a cold front passed over the state. At the same time, microseisms at Roosevelt Roads more than doubled in amplitude and two directions were obtained. This was a front causing high winds and much disturbed weather to the north and northwest. It should be noticed that the Guantanamo Bay station, between the other two stations, did not record any microseismic increase.

O, P, Q. These three places showed more or less increased microseismic activity. At Roosevelt Roads many bearings were obtained. Again aircraft reconnaissance discovered strong winds and disturbed areas. From the first of November there were a series of cold fronts and other disturbed atmospheric conditions that seemingly were the cause of large microseismic activity, first at one station, then at another.

The second major hurricane of the 1945 season developed east of Puerto Rico on September 12, passed north of San Juan and Guantanamo Bay and almost directly over the station at Richmond, Florida, as shown in figure 11. It provided the test for the microseismic equipment and technique that was needed to give final proof that the seismograph could *detect, locate, and track hurricanes*. This storm was the first one ever to be located simultaneously by cross bearings from two tripartite seismograph stations.

The September hurricane started with relatively high winds and very soon developed into what was classed as a "dangerous storm." It was picked up on the Roosevelt Roads station shortly after it was discovered by aircraft on September 12. The following day, the seismographs recorded a high of 20 mm. as the storm passed the nearest point. The seismograph continued to record large microseisms for thirty-six hours after the storm passed, but instrumental difficulties prevented dependable azimuths during all of this time. The bearings obtained, although not outstanding for accuracy, were always in the general direction of the strongest winds in the hurricane and shifted with the storm as it moved westward. (See fig. 11.)

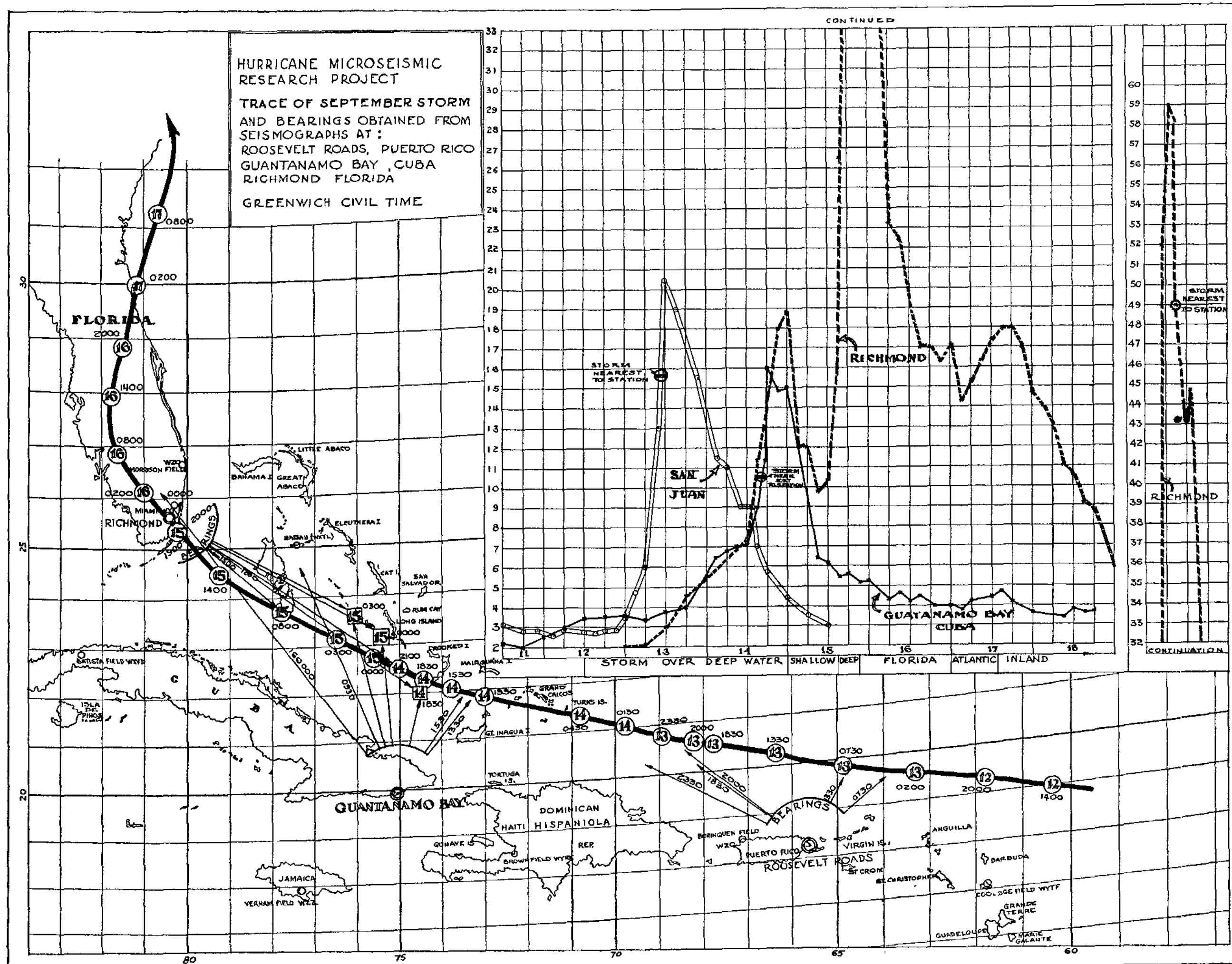

Fig. 11. Hurricane track and amplitude chart, September, 1945.

When the seismograph at Roosevelt Roads, Puerto Rico, was showing its highest microseismic activity, the stations at Guantanamo Bay, Cuba, and Richmond, Florida, started to increase slowly and reached a high of 17 mm. about midnight on the 14th. This maximum activity continued for six hours at both stations and then began to decline rapidly at a time when the storm was *receding from* Guantanamo Bay and *approaching* Richmond. This seemingly unorthodox behavior on the part of the Richmond station has two possible explanations. Figure 3 shows one possible cause for this decline. The storm was entering an area of very shallow water at the time the decline started. It would therefore appear from a careful study of this chart, which shows the tracks of major hurricanes during the past two years and the depth of water over which they passed, that the only time the depth of water has any influence on the amplitude of the microseisms is when it is not more than a few feet deep. The other reason, suggested by Gutenberg,[16] is that certain deep-seated faults tend to damp out microseismic waves as they try to pass from one geological block to another. Deep geological discontinuities greatly decrease (or damp out) the microseismic amplitudes by absorption, reflection, or diffraction of energy, especially in the supposedly deeply dissected Caribbean area. Several such occurrences probably due to this latter cause have been noted in the past two years and will be discussed later.

During the time Guantanamo Bay and Richmond were recording simultaneously large microseisms, several very excellent bearings were obtained, as shown in figure 11. This is the first time that cross bearings have ever been obtained from two tripartite seismograph stations at the same time. Three simultaneous cross bearings were obtained, and several other bearings from the two stations with only small differences in time of observation. The cross bearings in figure 11 are denoted by squares with the day and hour of observation along the directional lines from the two stations. One of these seismographic "fixes" appears to be about thirty miles from the nearest calaculated position of the storm as determined from a combination of all other data shown by circles in figure 11. The other two are possibly not more than ten or fifteen miles from the calculated center of the storm. These data indicate that it is something near the center of the storm that produces the microseisms. Attention is directed to the large number of bearings obtained on this storm by the three stations and how close they all come to cutting the hurricane track at a point very near its exact position. From these data it is inconceivable that surf pounding against a steep coast as suggested by Wiechert[17] and Gutenberg[18] could have anything to do with the cause and origin of these dominant microseisms.

The hurricane reached deep water again about noon (GCT) on the 15th.

[16] "On Microseisms." [17] *Op. cit.*

[18] "Die Seismische Bodenunruhe" and "On Microseisms."

Figure 11 shows how abruptly the microseisms increased at Richmond from a low of 10 mm. to more than 60 mm. in about seven hours. A few microseismic peaks reached 90 mm., which represents an actual ground displacement of almost 0.23 mm. as the storm approached the Richmond station. The highest readings were recorded about one hour before the storm reached maximum intensity over the station and while a large part of it was still over relatively deep water of the Gulf Stream. The microseismic activity at Guantanamo Bay continued to decrease, even after the storm reached deep water. While the hurricane was passing over Florida the amplitude of the microseisms at Richmond decreased from more than 60 mm. to 17 mm. and remained low for about thirty-six hours. Owing to instrumental difficulties and high ground water entering the vaults, bearings could not be obtained on this storm while it was over Florida. A small increase occurred in the microseisms as the storm entered the Atlantic south of Jacksonville, and then gradually decreased as the storm again recurved inland north of Jacksonville. The Richmond station recorded large microseisms from this hurricane for six days.

Another moderate hurricane developed south and southwest of Guantanamo Bay during the first few days of October, and was similar to the one of October, 1944. The seismograph recorded this disturbed area at least two days before it was classed as a hurricane on official weather maps. It may be true that there was no complete circulation in the area before it was officially reported on the weather maps, but the seismograph at Guantanamo Bay, nevertheless, indicated definitely that a disturbance of some nature was brewing south of the station on the last day of September. (See fig. 12.) The bearings gradually shifted more and more to the southwest, and on October 2 were pointing directly to the hurricane that appeared on official weather maps. The amplitude of the microseisms reached 11 mm. on September 30, and remained at about 8 mm. until October 3. During that time the storm was moving away from the station toward and into British Honduras. Roosevelt Roads did not show any effect of this storm; however, the microseisms at Richmond increased to more than 30 mm. Since bearings could not be determined at Richmond, owing to the instrumental difficulties mentioned above, it cannot be certain that this storm was the cause of the large increase in amplitudes. The author believes that the large microseisms recorded at Richmond were not caused by the storm. The instrument at Richmond did not show any large increase when the June hurricane was south of the west end of Cuba, indicating that somewhere in that vicinity there may be a major deep-seated fault which partly damps microseismic waves. Also, the microseisms recorded at Richmond are very similar to those produced by a cold front (fig. 13), being very irregular and of short period. Short-period microseisms usually indicate a near-by source, as at Richmond when winds are prevalent over the Florida Keys.

It would appear from data obtained in two years of research that there are

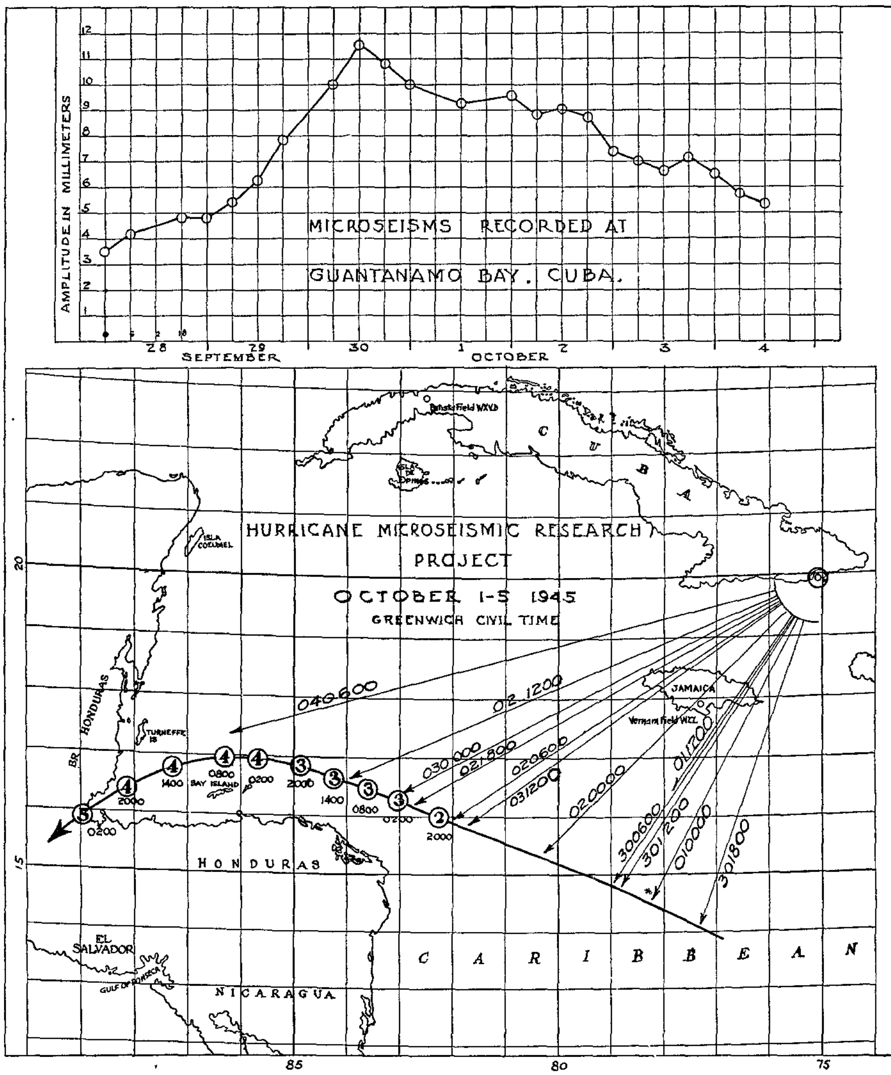

Fig. 12. Hurricane track and bearings, Guantanamo Bay, Cuba, October, 1945.

large geological blocks in the Caribbean-Gulf area, and that deep-seated faults separating them damp out a considerable part of the microseisms as they attempt to cross. The microseismic wave length is of the order of twelve to sixteen kilometers; hence, in order to damp out the microseisms, it is probable that the faults extend downward that distance or more. Also, the blocks on either side of the fault zone may be composed of radically different materials. It was considered that the storms of September (north of Cuba) and of

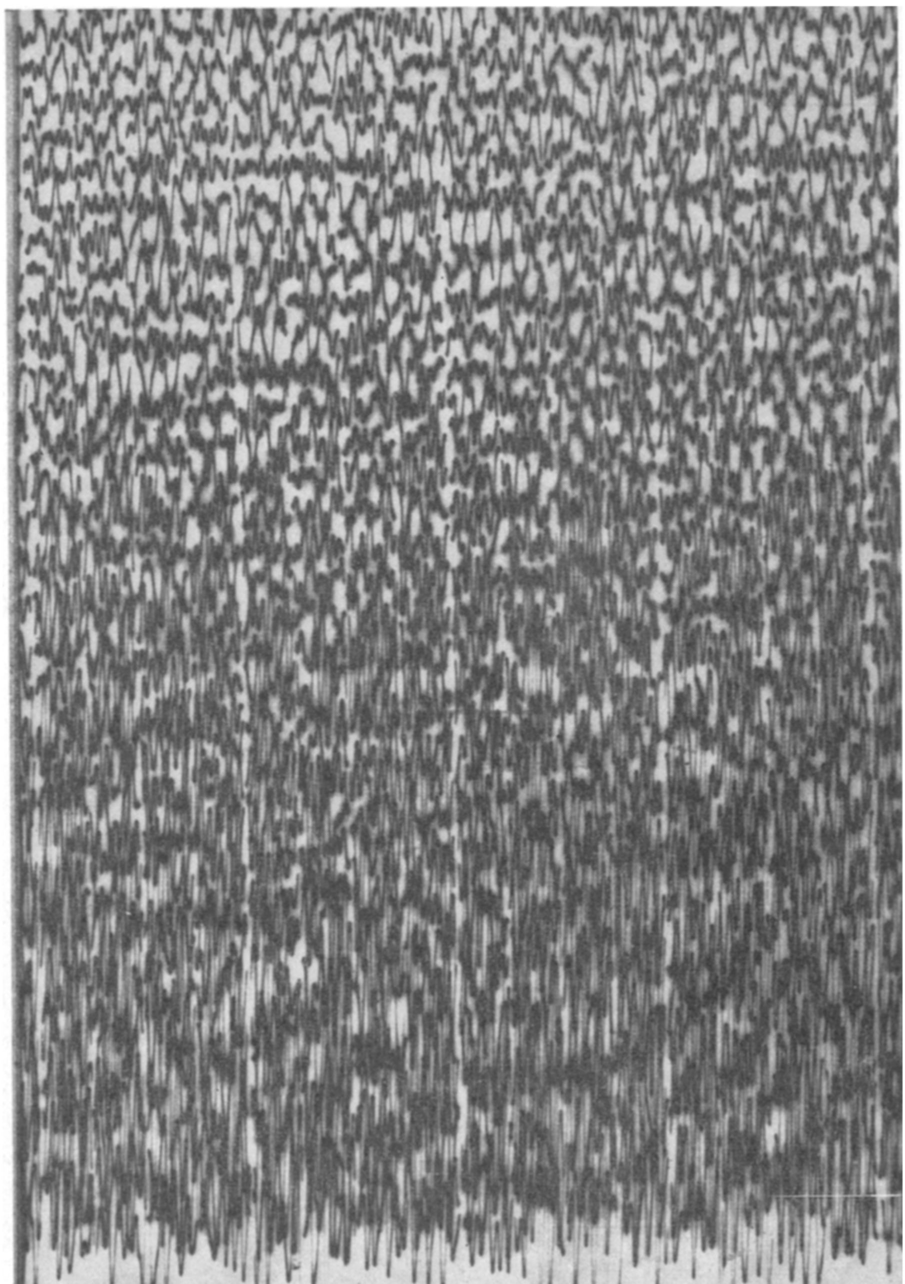

Fig. 13. Type of microseisms recorded durıng the passing of a cold front.

October (south of Cuba) in 1944 were of the same intensity and approximately the same distance from Guantanamo Bay, Cuba. The September storm gave a double-trace amplitude of 19 mm., and that of October, 55 mm. In addition, the storm of September, 1945, passing still closer to Cuba, and fully as strong as the storm of 1944, produced an amplitude of only 17 mm. These data indicate that there was some barrier between the tracks of the two storms to the north and the Guantanamo Bay station that was able to reflect, diffract, or absorb as much as 60 per cent of the microseismic energy. From these data the conclusion may be reached that a zone of demarkation in this area tends to damp out a considerable part of the wave motion. It could be a deep-seated fault. However, to the south (as indicated by the storms of October, 1944 and 1945) is a region, including the Guantanamo Bay tripartite seismograph station, that appears to be on the same large geological block, such as defined by Gutenberg.[19] From the scanty data at hand it appears that this fault zone runs along the northern border of Cuba all the way from some point north of Puerto Rico into the Gulf of Mexico. Figure 7 shows many increased microseisms coming from the southeast, south, southwest, and west of Guantanamo Bay. Somewhere along this fault zone the microseisms reaching Richmond are partly damped out. This is another argument in support of the geological block theory. As more data are collected from this area, these "fault" zones can be more accurately located and the records from the various stations in the Caribbean and the Gulf of Mexico will be more easily interpreted.

Conclusions

A special correlation study of microseisms and tropical storms has been made in the Caribbean and is very convincing. More than one hundred hurricanes have been studied for the years 1932 through 1944 in connection with the microseisms recorded at the United States Coast and Geodetic Survey Observatory at San Juan, Puerto Rico. During these thirteen years all the San Juan records have been measured for May–November. The data obtained in the correlation study definitely show many interesting and pertinent facts concerning microseisms and storms. It reveals that: (1) larger than normal microseisms were recorded for *each hurricane* that passed within three hundred miles of San Juan, regardless of intensity; (2) larger than normal microseisms were recorded for *more than 90 per cent of all hurricanes* that passed within 700 miles of the station; (3) larger than normal microseisms were recorded for about *90 per cent of all well-developed hurricanes throughout their entire tracks,* a few as much as 2,000 miles away; (4) many hurricanes, especially all the larger ones, were indicated by large microseismic activity at San Juan from one to three days before they appeared on official Weather Bureau maps; (5) conversely, large microseisms *were never recorded at San Juan* unless there was

[19] "On Microseisms."

some meteorological condition that could explain them. The tracks of some of the above-mentioned hurricanes are shown in figure 15, which also shows the relation between the microseismic amplitude and the hurricanes. Some of these storms passed over the shallow water north of Cuba, shown in figure 3, and, when doing so, would always show greatly reduced microseismic activity at San Juan. This study gave some indication of certain deep-seated fault zones in the area, but the data were insufficient to permit satisfactory conclusions.

As a result of two years' experimental work in the Caribbean on the Hurricane Microseismic Research Project for the Naval Aerological Service, it

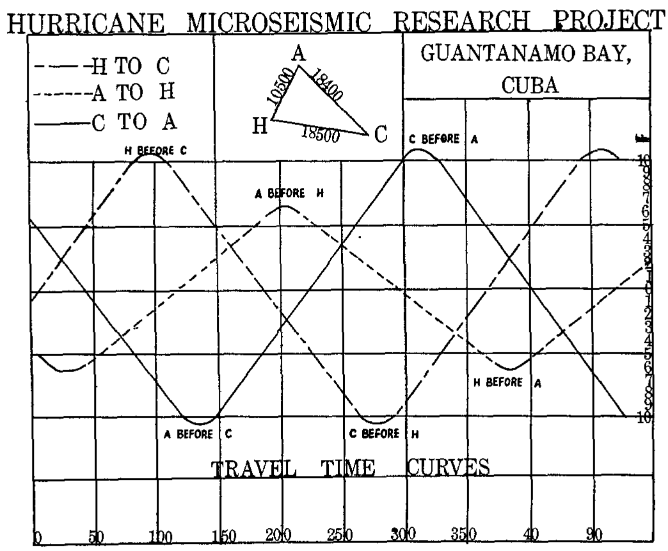

Fig. 14. Travel-time curves for three stations at Guantanamo Bay, Cuba.

would appear that the problem mentioned on the first page of this paper has been solved. Evidence in the form of statistical and observed data presented herein are considered conclusive in proving the validity of the microseismic theory advanced by Ramirez and others. This evidence indicates that the theory advanced by Wiechert, Gutenberg, and others, that more or less regular and dominant microseisms of two- to seven-second period are produced by surf *is not true.* The microseisms recorded in Puerto Rico, Cuba, and Florida, are definite evidence against this theory. No one has ever advanced a practical working method for forecasting and tracking storms on the basis of the surf theory. The data show that the microseims are, in some manner, caused by the storm itself and are transmitted directly from the central storm area to the various seismograph stations. The data strongly rule out even a possible chance that the dominant microseisms recorded during a hurricane could be associated with surf.

In general, the following detailed results of this research are outstanding:

1. Dominant microseismic waves of two- to seven-seconds period originate in some manner near the center of atmospheric disturbances.

2. Since this type of microseism is caused by atmospheric disturbances, such as hurricanes and extratropical low pressure areas, it is possible to tell of the

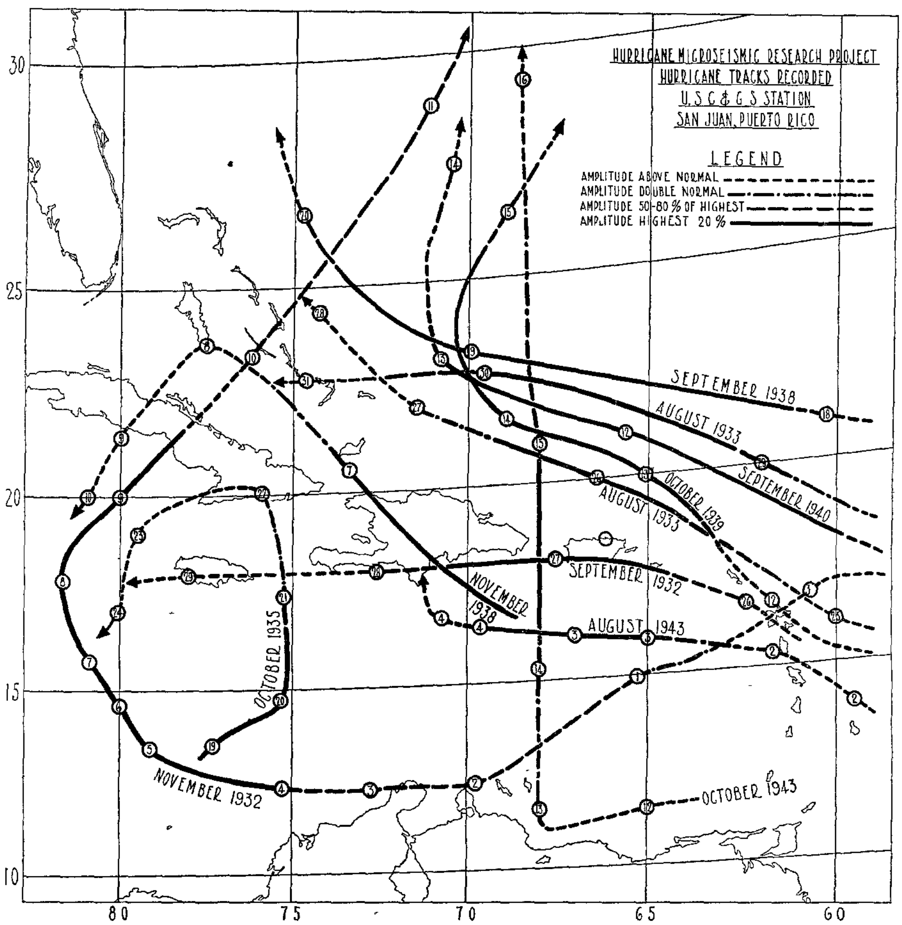

Fig. 15. Storm tracks in the Caribbean for 1932 through 1944; a few of 100 investigated.

existence of these near-by storms by an increase in microseismic activity at any *single component seismograph station.* It would, therefore, be impossible for a severe storm to approach a microseismic seismograph station without first giving warning sufficient to permit needed safety measures to be taken before it should arrive.

3. Since the tripartite seismograph station can *always* ascertain the direction of an atmospherically disturbed area as soon as it comes within range of

the station, it would be possible for two or more such stations to supply data sufficient for accurate location of the storm area and for plotting its movement during both day and night.

The author feels that the results of this research justify a belief that any type of meteorological disturbance almost regardless of intensity can be *detected* within a range of three hundred miles of a microseismic seismograph station and that this distance increases up to two thousand miles or more for major hurricanes and deep extratropical lows, especially when over water. He also believes that, with sufficient study and training, an observer *can* distinguish between the formation and existence of a hurricane, a cold front, or an extratropical storm.

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