ON MICROSEISMS*

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EVER SINCE the beginning of instrumental seismology the problem of microseisms has been a subject of investigation. While for most of the types of microseisms the cause is known, there is still no agreement among seismologists on the cause of the most common type, namely, the more or less regular microseisms with periods of from 4 to 10 seconds. They have been found everywhere that instruments with a magnification of more than 100 for sinusoidal waves with periods of a few seconds are used.

The amplitudes of these waves vary considerably. If simultaneous observations over a large area are studied, it is always found that somewhere near a coast the motion is a maximum, and that the amplitudes decrease inland.[1,2,3,4,15]† While near the coasts amplitudes of 10 microns (1 micron = 0.001 mm = 1μ) are nothing unusual, the central Asiatic stations very seldom report amplitudes exceeding 1μ. The average amplitudes at the stations close to the ocean in western Europe (Eskdalemuir, De Bilt, Paris, Hamburg) are more than five times the amplitudes of the central Asiatic stations (Ekaterinburg-Sverdlovsk, Makejewka, Irkutsk, Taškent, Baku, Tiflis). In North America, the corresponding maximum distances from the nearest coast are very much smaller, and, besides, there are only a very few stations in the region most distant from either coast. But the examples which have been investigated so far[2] show clearly the *decrease* in amplitudes from that coast where in a special case the large amplitudes are observed, toward the other coast. All investigations based on data covering a large area indicate very clearly that the maximum of the motion occurs almost simultaneously over a whole continent,[3] as far as it is noticeable. From these observed results it follows that the cause of these microseisms is not local and that it is much more powerful over the ocean or near the coast than over a continent. Many possible causes have been eliminated, such as the temperature, the amount of air pressure, especially its minimum, the barometric gradient, changes in air pressure, windstorms or rain (both of which occasionally cause irregular microseisms with shorter periods). There seem to be only two types of hypothesis which have been considered in recent years: one, suggested by E. Wiechert, that these microseisms are caused by the surf breaking on an extended steep coast,[2,6,7,12,14,16] the other, that the microseisms are connected with rapid changes in pressure caused either by the waves in the ocean[10,13] or by the "pumping" of the air pressure in cyclones, especially tropical cyclones.[8,11,12]

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† Superior numbers refer to items in the bibliography at the end of this article.

On the one hand Banerji[9,10] assumes that the energy of the ocean waves is propagated to the bottom of the ocean even where the water is very deep, and spreads from there in all directions through the ground; but such a transfer in energy through the water does not correspond to theory.[2] His second paper[10] does not remove the objections; according to a letter from Dr. A. W. Lee, this has been worked out in detail by English seismologists. On the other hand, Whipple[13] assumes that longitudinal waves are set up at the surface by the usual ocean waves and that these longitudinal waves travel across the water, and act then in the same way as has been suggested by Banerji. If this explanation is correct, large microseisms are to be expected in connection with each well-developed low-pressure area over the ocean. The observations, however, indicate clearly that this is not so. (See [4] p. 62, [14] pp. 11–12).

There are frequently well-developed low-pressure areas over the Pacific Ocean west of Pasadena, but no large microseisms are recorded there so long as the low-pressure area does not approach the continent so closely that surf can be produced against a steep coast. Usually the maximum microseisms are recorded at Pasadena when the disturbance crosses the Alaskan coast; usually it is then more distant from Pasadena than it was on the ocean, where, besides, it had steeper gradients. As an example we may quote the time interval October 24 to 27, 1935. During the first two days a low-pressure area (minimum about 29.2 in.) was situated about 1800 miles west of Pasadena over the Pacific Ocean. The maximum difference in pressure was about 1¼ inches. The microseisms at Pasadena remained at about ¼ μ. The following day, the low-pressure area moved toward the coast of Alaska, and passed it on October 27/28 near 60° N and 140° W. Although the low-pressure area decreased in intensity, and its distance from Pasadena increased, the microseisms increased to nearly 1 μ when the low-pressure area passed the coast of Alaska. Again, between November 17 and 21, 1935, a marked low-pressure area was situated over the Pacific Ocean northwest of Pasadena, with a minimum of about 29.2 inches on November 18, distant about 1200 miles from Pasadena. Once more the microseisms remained small (continuously less than ½ μ).

On May 23, 1935, a low-pressure area with steep gradients and a minimum of about 29 inches had its center about 500 miles south of the Aleutian Islands. The microseisms on that day were about ½ μ. They increased to about 1½ μ when the low-pressure area approached the coast of Alaska two days later. On the first day there was also a secondary low-pressure area with its center about 200 miles northeast of Pasadena. Such low-pressure areas never produce large microseisms of the type under consideration, but irregular waves with very much shorter periods resulting from windstorm or surf on the local coasts, or still shorter waves caused by rain (not necessarily at the station itself) are frequently superimposed on the normal microseisms. (Examples, July 1 and November 2, 1935: center of low pressure 29.6 inches, distant a few hundred miles north or northeast of Pasadena, normal microseisms not over $\frac{1}{2}\,\mu$). High surf in the neighborhood of Pasadena does not increase the microseisms very much, but apparently produces only relatively small waves with periods of a second or two.

These and other data indicate clearly that the presence of a low-pressure area alone is not sufficient to produce microseisms; in general they become large in Pasadena as soon as a marked low-pressure area passes the coast of Alaska or British Columbia. The results, therefore, are not in favor of the theory that the ocean waves or the "pumping" of the pressure over the ocean generate these movements. That there is no correlation between the local surf and the microseisms, however, does not disprove the hypothesis that the surf along *steep coasts* is the cause of the movements, as believed by Bradford.[11] His table 1, in which he compares the local surf near Sitka (unfortunately he gives no details about the source of these data) with the microseisms recorded there contains 102 pairs of values. In three, the surf was 1 unit larger than the microseisms, in one it was 2 units larger, in all the other 98 it was equal or smaller. These four notations are certainly within the limits of error. That heavy surf is accompanied by large microseisms is rather in favor of than against the "surf theory." Large microseisms, of course, may be produced by heavy surf at parts of the coast other than near Sitka.

The first step in proving a theory concerning microseisms is to show that the order of the energy required to produce the microseisms is correct. The author believes that this has been done for the surf theory.[2] Bradford[11] has repeated the calculation with different assumptions, but even his calculation gives the right order (0.316μ) although he assumes that the energy of a sinusoidal wave with the amplitude 1 equals 1, and that the length of the coast struck by the surf at angles between about $+45°$ and $-45°$ (average cosine 0.8) is only 200 kilometers, which is clearly too small. Of course, only the order of the amplitudes can be found in this way, especially since the percentage of energy which is transferred by the surf to the coast is not exactly known. The author in his previous paper[2] had assumed that 10 per cent of the surf energy goes into the vibrations of the coast, but the fact that the calculated amplitudes of the microseisms (order 50μ) come out rather high indicates that only a smaller fraction of energy is transferred to the coast. Bradford[11] assumes 0.1 per cent only.

The question which has puzzled most of the investigators of these microseisms is the problem of how the periods originate. The explanation given repeatedly by the author[1,2] apparently has escaped attention. According to his view, the coast is shaken by the surf. The vibrations are irregular with pseudo-periods ranging from a fraction of a second to several seconds. At near-by stations these irregular waves are recorded, as is shown by many observations at stations near the coast (e.g., Helgoland, Apia, Zikawei, La Jolla). In agreement with the theory (see, for example, [2] p. 2), the waves become longer and flatter as they are propagated, and the irregularities disappear. The records agree with these results.[1,3] The question of the origin of the periods has been raised usually only in connection with the surf theory, but it is just as important for other theories. Bradford[11] has suggested a study of the periods of the atmospheric oscillations ranging from a fraction of a second to as much as 6 or 7 seconds. Such an investigation would be interesting, but would not help in the solution of our problem, for here, too, "the waves would not occur simultaneously . . . and consequently the agreement between the periods of the microseisms and the . . . waves [here the atmospheric oscillations] is not explained" [if it could be shown].[4,11]

Several recent publications are either in favor of the "surf theory" or give results which may easily be explained by it. Frequently the statement can be found that the microseisms increase when a low-pressure area crosses the coast. In such occurrences the surf possibly (not "surely";[11] p. 339) was the cause. But Tams's[6] finding of a correlation coefficient of 0.8 or more between the surf in Norway and the microseisms in Hamburg and K. Jung's[7] finding of a similar good correlation between the surf in Norway and the microseisms at Potsdam, besides the many correlations of similar type published previously,[1,15] indicate that the surf very probably is the cause. The result given by Bradford,[11] that there is no close correlation between the local surf near Sitka and the microseisms there, should be compared with the result of Tams, that there is no good correlation between the surf at the coasts near Hamburg and the microseisms at Hamburg—although, as just mentioned, the correlation with surf in Norway is excellent. Difficulties in studying these problems are that no data on the surf on the coasts of North America are regularly published, and that it is difficult to find the coasts where large surf produces strong microseisms at a given station.

An interesting investigation on the direction from which the microseisms seem to arrive has been published by A. W. Lee.[5] His conclusion is that the direction of arrival is inconsistent with the theories that the oscillations are caused by the action of wind or waves on steep coasts, or by the motion of waves over shallow water, but he does not indicate the reason for this conclusion very clearly. In his "case b)" only, he remarks that the rough seas in northern Norway are very favorable for the generation of microseisms according to the "surf theory," but that the relatively small amplitude at this time does not support the hypothesis. Apparently he has overlooked the view that the surf in northern Norway, according to the results of the author,[1,3,15] is of large importance only for stations in northern Europe and in northern and central Asia. The microseisms are propagated well in Europe only if the source and the station are in the same geological unit. A map given by the author (for example in [1] on p. 293, in [3] on p. 106) indicates clearly that in his opinion the microseisms at Kew are caused mainly by the surf around Britain. The maps and the data published by Lee show a good agreement between the direction of the microseisms which he found and the direction of the coast which probably was struck by strong surf, considering the weather conditions. His "figures 8, 9, and 10 show stormy conditions around Norway, but the phases of the microseisms emphasize that the movements must have originated north-west of Kew." But looking at his weather maps, one sees that very probably there was strong surf on the west and north coasts of Britain, connected with strong winds against large parts of the coasts. This latter fact is essential, as only surf driven against a steep coast and not the occurrence of strong surf alone produces large microseisms. Thus, Lee's results are rather in favor of the "surf theory" than in favor of any theory in which a direct effect of the low pressure is supposed, as "the regions in which the microseisms were produced are not affected by the position of the depression" ([5] p. 197).

As has been mentioned already, Gherzi[8] believes that the "pumping" in typhoons is essential in the producing of microseisms. Bradford[11] tries to extend this explanation, as has been done by Gherzi, to the low-pressure areas in more northern latitudes. Such a pumping effect is observed there, too, but it exists just as much when the cyclones have passed the coast. Why, then, do microseisms generally decrease as soon as the low-pressure area has passed the coast from the ocean toward the land? The microseisms should reach their peak about the time when a low-pressure area passes the station, since at that moment the distance of the supposed source is a minimum. The observations, however, show that the maxima of the microseisms occur simultaneously over large areas and clearly are not connected with the passing of low-pressure areas over the individual station.

In a recent paper[12] W. C. Repetti has expressed the opinion that the microseisms at Manila are produced in both ways, by the surf and by the "pumping" in a typhoon, although he gives no definite evidence for his hypothesis.

> The wind of the approaching typhoon sets up a sea which, breaking on the coast of Luzon, causes microseismic vibration. When the typhoon comes within a certain distance of Manila the oscillations of the earth's crust produced by the pumping effect make themselves felt and combine with those set up by the sea. The result is a great increase in amplitudes of the microseisms and an accentuation of the group or beat effect.

K. Wadati and K. Masuda have found recently[16] that in Japan "the main cause of generating ordinary microseisms is the breaking effect of strong waves at the sea-shore."

The effect of a tropical cyclone could be studied at Pasadena by use of the seismograms in August, 1935. On the 5th, 6th, and 7th the microseisms were very small, their amplitudes being about 0.2μ. On the 8th they increased slowly, and reached about 0.3μ in the morning of the 9th. In the night of the 9th/10th they increased more rapidly, and on the 10th very many waves had amplitudes of $1\frac{1}{4}$ to $1\frac{1}{2}$ μ. Such amplitudes occur occasionally in winter months, but are extremely rare in August. The next night, the amplitudes decreased again; they fell below 0.5μ on the 11th, and reached the normal value about the 13th.

During the whole time, there was no major disturbance near California; the wind velocity was very small there; the only cause of the microseisms could have been a tropical disturbance reported from the coast of Mexico south of Lower California. According to the weather map of the Servicio Meteorologico Mexicano and to ship reports published by the United States Weather Bureau, this cyclone formed about August 5 near 18° N, 103° W. On this and the following day, the cyclone was recognizable more by strong winds (intensity 8–10 of a scale with a maximum of 12=hurricane) than by the isobars. The direction of the wind near the coast was E to SE (toward the ocean or parallel to the coast). Between the 7th and the 9th the cyclone increased in intensity and seems to have reached its largest extent on the 9th, with its center near 20° N, 113° W. During this whole time interval the wind near the coast continued to be E to SE with maximum velocities of 10. The minimum air pressure observed was about 751 mm. (29.6 in.) and the maximum difference in pressure apparently never exceeded 10 mm. (0.4 in.). On the 10th the cyclone moved to the westward, apparently decreasing in intensity, and no trace of it remained on the morning of the 11th. During the 10th there were still winds of intensity 10, but blowing now toward the coast. They decreased the following day, and on the 12th the wind died down completely.

This cyclone was distant from Pasadena about 15° (1000 mi.), and about 18° from Tinemaha, where the maximum of the microseisms is about at the same time as at Pasadena. There is no doubt that neither the small change in pressure, nor its relatively small gradient, nor the wind, which was "violent" during several days, can have produced the microseisms. There is no reason to assume that the "pumping effect" should have been larger on August 10th than on the 8th/9th when the cyclone had its maximum intensity, but it is very reasonable to suppose that on the 10th the surf was at its maximum, produced by the waves which had been increased during the preceding days by the storm and were now driven by the wind against the coast.

All the preceding arguments have not "proved" that the surf is the cause of the microseisms, but, so far, no other cause has been suggested which fits the observations equally well and has the energy necessary to produce elastic waves over a whole continent. It is especially to be noted that as soon as large ocean waves are driven by a storm against a steep coast, the microseisms appear in the whole area connected geologically with that coast. Where sufficient observations of the surf are available, and the correct coast has been found, the correlation between the surf and the microseisms is excellent (more than 0.8 between the surf in Norway and microseisms in northern and eastern Europe). Unfortunately, in America no observations of the surf are published for a number of stations large enough to locate the active regions more accurately. 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 main 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. Other causes may be involved, but so far as detailed studies have been published which allowed comparison of the microseisms at several stations of a given area with the corresponding weather maps, no good correlation with other elements providing sufficient energy has been found. It is well known, however, that microseisms of various other types are produced locally by various meteorological elements and other causes.

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