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MICROSEISMS IN NORTH AMERICA

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INTRODUCTION

Our most sensitive seismographs are never at rest. They show that there are always small movements of the earth's crust which are called "microseisms." Investigations (1) have shown that there are different kinds of such movements, caused by traffic, industry, wind, rain, waterfalls, waves beating against the coasts, freezing of the soil, and probably some other causes. In the following we shall deal only with that kind of microseisms which is characterized by a regular, nearly sinusoidal motion with periods in general between four and ten seconds. These have been found throughout the world.

In Europe this kind of motion occurs whenever a low-pressure area approaches the western coast and causes high surf against steep coasts. The pressure itself does not produce the motion, as has been shown in many cases, neither when its center is over the sea nor when it is over the continent (2). There the movement is propagated over the whole continent and even far into Asia (9). High surf against the coast of Norway is always recorded even as far as Irkutsk in the heart of Asia. In this case the whole northern half of Europe and the western half of Asia show vibrations of nearly the same period, ranging in general from six to eight seconds. High surf in other parts of Europe does not produce so large movements, since on the one hand steep rock coasts are not so extensive there and on the other hand the structure of the earth's crust is very irregular in the southern part of Europe. The movements apparently pass very easily across the shields in northern Eurasia, but the waves are reflected and refracted when passing through the southern part with its folds and areas of disturbed young mountains.

For other parts of the world such investigations have been less extensive. Linke (3) was the first who tried to use seismograms to predict storms. He always found increasing motion of this kind at Apia

(Samoa), when a storm approached, especially when high waves reached an island. From the appearance of the microseisms and changes in them he was able to draw conclusions as to the path of the storm. He was convinced that only surf against the islands could have caused the movements, following the hypothesis of Wiechert who had first expressed the opinion that all such movements are produced by the surf against steep, rocky coasts. Many other hypotheses have been offered, but most of them have been disproved. Besides the view of Wiechert, in recent years the theories of chief interest have been those of Biot (4), Gherzi (5), and Banerji (6), who thought that either changes of air-pressure or the changing pressure of the sea-waves are propagated through the water of the ocean to its bottom and from there to the continents where these movements are recorded as microseisms. But that these cannot be due only to variations of air pressure in low-pressure areas, as Gherzi believes, is shown by the observations of Banerji, who observed microseisms at Bombay in the case of monsoons, as well as with storms, but with a slightly different aspect. That such changes of pressure cannot be propagated through the water of the ocean at all will be shown in the last part of this paper.

Of especial interest to us is the fact that Gherzi found that these movements occur in Shanghai whenever a storm is approaching the coast, but that they diminish very rapidly as soon as the storm has passed the coast. The same result was found by Banerji in the case of microseisms recorded at Bombay. As mentioned above, he there observed microseisms of a similar kind in the case when the monsoon caused rough sea along the coast near his station. But we know since the investigations of Linke that the motion everywhere is less regular the nearer the disturbance is to the recording seismograph. The motion becomes smoother as it proceeds and the periods increase according to the theory. The normal and tangential stresses (N and T) in an elastic body with internal friction are given by equations of the following form (7), (12), (13):

$$N_1 = \lambda\Theta + 2\mu\frac{\partial u}{\partial x} - \tfrac{2}{3}\eta\frac{\partial\Theta}{\partial t} + 2\eta\frac{\partial^2 u}{\partial x\partial t}$$

$$T_1 = \mu\left(\frac{\partial w}{\partial y}+\frac{\partial v}{\partial z}\right) + \eta\frac{\partial}{\partial t}\left(\frac{\partial w}{\partial y}+\frac{\partial v}{\partial z}\right)$$

The general solution of a system of such equations was first given by Sezawa (12). He finds: "However sharp the initial form of disturbance may be, the pulses in visco-elastic solid bodies take gradually flat forms, their apparent wave-length being prolonged." If we suppose especially a surface wave of sinusoidal form, we find according to Gutenberg and Schlechtweg (13) in the first approximation the following equation between the period T_0 at the origin and the period T at a distance Δ

$$T^2 = T_0^2 + \frac{2\eta\Delta}{V^3}$$

in which η = coefficient of internal friction, and V = velocity of waves. If we put $\eta = \mu\varkappa$, in which μ = modulus of rigidity, and consider that in the case of short surface shear waves (and in the first approximation also in the case of short Rayleigh waves)

$$V^2 = \mu/\delta \qquad \delta = \text{density}$$

we get

$$T^2 = T_0^2 + \frac{2\varkappa\delta\Delta}{V}$$

The velocity of microseisms seems to be somewhat larger than three kilometers per second. So we get from theory in the first approximation in the case of microseisms with periods of a few seconds

$$T^2 = T_0^2 + 6\eta\Delta \times 10^{-12} = T_0^2 + 2\varkappa\Delta$$

in which Δ is measured in kilometers.

Observations of η and $\varkappa$ are very rare. For example the following values have been found (13)

	Fe	Cu	Ag	Au	Al	Sn	
η	1.4	0.6	1.2	1.7	0.3–2.5	3.6	$\times 10^9$
$\varkappa$	0.002	0.002	0.004	0.006	0.001–0.008	0.02	

Using $\eta = 1\frac{2}{3} \times 10^9$ or $\varkappa = 0.005$ we get as a first approximation for our waves

$$T^2 = T_0^2 + 0.01\Delta \text{ (km.)}$$

From this equation we find the following increase of period in seconds with distance:

Δ(km.)	100	500	1,000	5,000
	s	s	s	s
$T_0 = 0.1$ s	1	$2\frac{1}{4}$	3	7
$T_0 = 1$	$1\frac{1}{2}$	$2\frac{1}{2}$	$3\frac{1}{4}$	7
$T_0 = 4$	4.1	$4\frac{3}{4}$	$5\frac{1}{4}$	$8\frac{1}{4}$

The order of these values agrees very well with the observations.

In America we do not know very much about microseisms of this kind. Klotz has dealt with them, and he found that the amplitudes of this kind of motion generally reach their maximum at Ottawa, Canada, when a low-pressure area passes over the St. Lawrence Gulf (8).

To get a similar understanding regarding microseisms in North America to that already obtained for Europe, four intervals of several days each with a different location of the area of low pressure and storm were selected, and the more important seismological observatories of the United States, Canada, and Mexico were requested to lend their seismograms covering these intervals. In a few cases the seismograms of a fifth period were used, during which extremely large microseisms had been observed at St. Louis, as indicated in the bulletin of that station. Graphs were sent by the following stations:[1] Sitka, Chicago, Tucson, and Charlottesville (all by courtesy of the United States Coast and Geodetic Survey); St. Louis and Florissant (both St. Louis University); Milwaukee (Marquette University); Ottawa, Seven Falls, and Saskatoon (by courtesy of the Dominion Observatory, Ottawa, Canada); Victoria, B.C. (Dominion Meteorological Observatory); Berkeley and Lick Observatory (by courtesy of the Seismological Station of the University of California); Pasadena (Seismological Laboratory) and auxiliary stations in southern California using short-period instruments which generally cannot be used for this purpose; Cambridge, Massachusetts (Seismographic Station of Harvard University) and Washington, D.C. (Georgetown University).

It is a pleasure for the writer to record his appreciation of the assistance he has received from the directors and seismologists of the institutions and observatories mentioned above, to the Chief of the United States Weather Bureau, Washington, D.C., and its offices at Los Angeles and San Francisco for assistance in providing necessary weather maps and also to Mr. H. O. Wood for correcting the English style.

The stations at Toronto and Buffalo were equipped only with instruments of low magnification (the latter now has Galitzin pendulums), which recorded no microseisms; at Spring Hill College, Mobile, Alabama, and Santa Clara, California, the instruments were not operating during the intervals for which microseisms were studied, and at Regis College, Denver, Colorado, and at Halifax only those seismograms are saved which show interesting records. No answers were received from eight other stations.

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[1] The location of the stations may be seen in Figure 4.

In all cases the periods and the largest amplitudes which occurred during an interval of a quarter of an hour at approximately 0^h, 4^h, 8^h, 12^h, 16^h, and 20^h, Central Standard Time, were measured for every day. In most cases the constants of the instruments were not known very accurately. Besides, the amplitudes are influenced by the subsoil of the stations. Therefore the same method of research was used as has been employed in Europe (9) : The horizontal component of the motion was calculated from the north-south component (N) and the east-west component (E) by the formula $H^2 = N^2 + E^2$. Then in every one of the four cases mentioned above the maximum amplitude was noted and the mean maximum, M, of these four values calculated. Finally all horizontal amplitudes of every station were divided by the corresponding values of M and thus relative amplitudes A were found. These values were used in the following study. As has been pointed out in the investigation (9) mentioned above, this method has the advantage that errors in the determination of the magnification of the instrument and the effect of the subsoil are eliminated, but on the other hand a factor influenced by the distance from the source of the motion is lost.

General Results on Microseisms in North America

The chief intervals for which data were used are, 1930, January 2–6, March 6–10, March 13–17, March 24–28, and at a few stations January 28–31. Only the four periods mentioned first were used in calculating M. Table I shows the absolute maxima of the horizontal amplitudes during these intervals. The differences are partly due to errors in the magnification calculated for the various instruments, partly to the effect of the subsoil.

TABLE I

Maxima of the Horizontal Component of the Amplitudes in μ

Sitka 7	Saskatoon 8(?)	Milwaukee ..8	Ottawa 3	Seven Falls 3½
Victoria 4½	....	Chicago 7¾	....	Cambridge ..5
Berkeley ...2¼	Lick 2½	Florissant ..2½	St. Louis 2	Washington (3)
Pasadena ...2½	Tucson 1½	....	Charlottesville 3½	....

In northern and southern Europe the east-west component is somewhat larger. In the intervening east-west zone the north-south component prevails in some degree. Table II (p. 6) shows the corresponding values in America. The number and quality of the observations are not yet sufficient to yield definite results.

The ratio of the horizontal to the vertical component could be calculated only from the seismograms at Florissant, where in general it was in the neighborhood of two (in Europe it is generally between one and four at the various stations).

TABLE II

RATIO OF NORTH-SOUTH COMPONENT TO EAST-WEST COMPONENT

Victoria 0.8	....	Chicago 0.9	Ottawa 0.9	Cambridge ..1.1
Tucson 1.0	Florissant 1.2	St. Louis ...0.9	....	....

The periods of movement were generally between four and nine seconds. Only near the coasts do movements with shorter periods occur also, probably due to local surf. In Eurasia the periods generally increase with the distance from the shore. In America the highest values seem to occur in general in the interior of the continent, as is shown in Table III. Sometimes the periods increase when the amplitudes enlarge. We shall deal with this matter when we consider specific cases (Fig. 2, p. 13).

TABLE III

PERIODS OF MICROSEISMS

Mean of January 3rd, 0^h; March 3rd, 16^h; March 9th, 4^h; and March 26th, 12^h

Sitka 5.4	Saskatoon ..5.3	Milwaukee 6.0	Ottawa 7.3	Seven Falls 6.9
Victoria 6.9	....	Chicago 7.4	....	Cambridge ..7.0
Berkeley ...6.3	Lick 6.3	Florissant ..7.0	St. Louis.....6.0	Washington 6.5
Pasadena ...6.3	Tucson 7.3	....	Charlottesville 6.5	....

MICROSEISMS ASSOCIATED WITH STRONG WINDS ON THE WEST COAST

On January 2, 1930, a very marked low-pressure area with steep gradients approached the coast of Alaska near the Queen Charlotte Islands and passed on to Alberta during the night of January 2nd and 3rd. A new disturbance of similar nature appeared in the same region, but this moved southward, its center being west of Victoria on the morning of the 4th, whence it moved slowly to the southeast. As can be seen in Table IV, the microseisms correspond very well with the movement of the disturbance, but they are not propagated very far into the interior of the continent, although a slight increase of the amplitudes during the storm on the northwest coast is rather clear at nearly all stations. The periods did not change very much during the whole time. On January 2nd and 3rd they were approximately six seconds at all stations and at most of them they decreased to five or even four seconds during the 4th and 5th.

Now the question arises whether storms at some distance from the shore may cause microseisms. Our observations show that they do not. There is nearly always a marked low-pressure area over the Pacific, some hundred miles west of the coast, but microseisms do not begin until such a disturbance is near enough to the coast to cause high surf.

TABLE IV

RELATIVE HORIZONTAL AMPLITUDES (AMPLITUDES: *M*, COMPARE P. 5) FROM JANUARY 2 TO 6, 1930

	$2^{d}0^{h}$	$2^{d}12^{h}$	$3^{d}0^{h}$	$3^{d}12^{h}$	$4^{d}0^{h}$	$4^{d}12^{h}$	$5^{d}0^{h}$	$5^{d}12^{h}$	$6^{d}0^{h}$
Sitka	0.3	*1.5*	0.6	0.2	.1	0.1	0.1	.1	.1
Victoria	0.7	0.8	*1.9*	*1.2*	.7	0.6	0.3	.3	.2
Berkeley	?	?	?	0.4	.5	*1.4*	0.8	.8	.5
Lick	?	1.0	1.0	1.0	.6	*1.2*	*1.6*	.8	.6
Pasadena	0.7	0.6	0.7	0.6	.6	0.5	0.4	.4	.5
Tucson	0.8	0.8	0.7	0.3	.3	0.3	0.3	.3	.3
Saskatoon	?	0.4	0.4	0.4	.4	0.4	0.2	.2	.2
Chicago	0.4	0.3	0.5	0.3	.2	0.2	0.2	.2	.2
Florissant	?	0.3	0.6	0.6	.3	0.3	0.3	.3	.3
Ottawa	?	0.5	0.7	0.5	.3	0.3	0.3	.4	.3
Seven Falls	?	0.6	0.6	0.2	.1	0.1	0.1	.1	.2
Cambridge	0.4	0.5	0.5	0.3	.4	0.7	0.5	.4	.4
Washington	0.7	0.6	0.6	0.7	.5	0.6	0.5	.5	.4
Charlottesville	?	?	0.2	0.2	.2	0.2	0.2	.2	.2

Low-pressure areas move over the region of southern California at rather rare intervals. On March 13, 1930, a low-pressure area with a minimum of 29.6 inches[2] covered western Nevada. During the day and the following night it developed on its western side, and in the morning of the 14th two centers with minima of 29.4 inches were located one 100 miles northwest of San Francisco and the other over southwestern Nevada. During the following twenty-four hours these depressions moved southeastwardly along the coast of California. During the 16th they flattened out and then disappeared during the following days, when they continued to move southeastwardly.

During this period all the stations of southern California showed rather large microseisms with short periods, one-half to four seconds. Two of them, Santa Barbara and La Jolla, are included in Table V (p. 8), which gives the relative movements during the dates mentioned above. As in the preceding case, it will be seen that the movements follow

[2] 1 inch = 25.400 mm; 29.0 inches = 736.6 mm; 29.5 inches = 749.3 mm; 30.0 inches = 762.0 mm.

very closely the development of the low-pressure area as it moved along the shore. Probably there is also a slight connection between the stations near the center of the storm and the more distant stations. Though no other low-pressure area covered the continent during these days, most of the stations showed somewhat larger microseisms than usual. One must keep in mind that number 1.0 means that the amplitudes of the microseisms reached the mean maximum of the four time-intervals considered.

TABLE V

AMPLITUDES OF THE MICROSEISMS (UNIT SAME AS IN TABLE IV)
MARCH 13–17, 1930

	13^d0^h	13^d12^h	14^d0^h	14^d12^h	15^d0^h	15^d12^h	16^d0^h	16^d12^h	17^d0^h	17^d12^h	18^d0^h
Sitka	*1.4*	*.9*	.6	0.2	0.2	0.2	0.2	0.3	0.3	0.3	.3
Victoria	0.5	.6	.7	*0.8*	0.6	0.5	0.3	0.3	0.3	0.2	.2
Berkeley	0.5	.5	.5	*0.9*	*1.0*	*1.4*	*1.2*	0.5	0.5	0.5	.3
Lick Observ. ..	0.2	.2	.2	*0.8*	0.6	0.6	*1.0*	0.6	0.4	0.0	.0
Santa Barbara..	0.2	.1	.1	0.4	0.5	*2.0*	*0.8*	0.4	0.1	0.3	.7
Pasadena	0.3	.4	.3	0.4	0.5	*0.8*	*0.8*	*1.1*	*1.4*	0.5	.7
La Jolla	0.1	.1	.1	0.4	0.5	0.3	0.3	0.1	0.2	0.1	.1
Tucson	0.1	.1	.4	0.5	0.7	*0.8*	*1.2*	*1.3*	*1.3*	*1.2*	*.9*
Saskatoon	?	*.9*	*.9*	*0.9*	*0.9*	*0.9*	0.6	0.6	0.6	0.6	.6
Chicago	0.6	.5	.3	0.3	0.3	0.6	0.5	0.4	0.3	0.3	.2
Florissant	0.3	.3	.3	0.3	0.3	0.7	0.6	0.6	0.3	0.3	.3
St. Louis	?	.5	.5	0.5	*0.8*	*0.8*	0.6	*0.8*	0.5	0.5	?
Milwaukee	0.3	.3	.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	.3
Ottawa	0.4	.4	.4	0.4	0.4	0.6	0.6	0.6	0.6	0.5	.3
Seven Falls ...	0.2	.2	.2	0.4	0.6	0.5	0.7	0.6	0.6	0.5	.2
Washington ...	0.5	.5	.4	0.4	0.5	0.7	0.5	0.6	0.4	0.7	.3
Charlottesville ..	0.4	.5	.4	0.4	0.4	0.7	0.4	0.2	0.2	0.2	.2

The periods of movement did not change very much during the five days. In most cases they were approximately six seconds, except in two instances at stations near the coast which have short-period instruments whose harmonic magnification is too small to record microseisms with periods of more than five seconds.

MICROSEISMS ASSOCIATED WITH STRONG WINDS NEAR THE EAST COAST

In the morning of March 6, 1930, an extended low-pressure area with a minimum of less than 29.35 inches covered the center of the United States. During the day and the following night it moved eastwardly with increasing intensity. In the morning of the 7th the center, now nearly 29.2 inches, covered Kentucky, lying between the observatories at St. Louis and Charlottesville. Then it turned in a more northeasterly direction, increased still more and reached the coast of the Atlantic near New York in the morning of March 8th with a minimum of 29.0 inches. In the course of the following two days the low pressure moved slowly northeastwardly along the coast. On March 9th, at 8: 00 a.m. the center was somewhat east of Portland, now 29.0, and on March 10, at 8: 00 a.m. north of Newfoundland, Belle Isle, now 29.1 inches. The gradients decreased slightly during these two days. During the 9th the depression continued to move northeastwardly and what remained is just noticeable in the northeast corner of the United States Weather Map of March 11th. In the interim a new low-pressure area had formed over the continent. Its center, 29.6 inches, was located west of Chicago in the morning of the 9th, grew deeper during the day, and in the morning of the 11th a very marked low-pressure area with steep gradients and a minimum of 29.1 inches had its center over the north end of Lake Michigan.

Now let us consider the microseisms during this time. Table VI gives their amplitudes in the same units as shown in the instances cited before. One recognizes that neither the low-pressure area which cov-

TABLE VI

AMPLITUDES OF MICROSEISMS, MARCH 6 TO 11, 1930 (UNITS AS IN TABLE IV)

	6^d0^h	6^d12^h	7^d0^h	7^d12^h	8^d0^h	8^d12^h	9^d0^h	9^d12^h	10^d0^h	10^d12^h	11^d0^h
Sitka	.2	.2	.6	.9	.6	.3	0.3	0.4	.4	.2	.6
Victoria	.6	.4	.4	.5	.6	.4	0.5	0.4	.4	.4	.4
Berkeley	?	?	?	?	?	?	?	0.5	.5	.4	.4
Pasadena	.9	.7	.5	.5	.5	.5	0.4	0.6	.7	.3	.3
Tucson	.5	.4	.4	.4	.4	.4	0.5	0.7	.4	.1	.1
Saskatoon	.8	.8	.9	.9	.8	.9	0.9	0.9	.9	.9	.9
Chicago	.3	.2	.2	.2	.3	.5	0.7	0.7	.7	.5	.4
Florissant	.3	.3	.3	.3	.3	.3	*1.0*	*1.0*	.4	.4	.4
St. Louis.......	.4	.4	.4	.4	.5	.6	*1.3*	*1.2*	.8	.8	.6
Ottawa	.3	.3	.3	.3	.4	.4	*1.0*	*1.2*	.6	.6	.4
Seven Falls	.1	.1	.1	.1	.1	.1	*1.2*	*1.2*	.5	.7	.4
Cambridge	.1	.1	.1	.1	.2	.9	*1.6*	*1.7*	.8	.6	?
Washington	.3	.2	.2	.2	.6	.9	*1.5*	*1.0*	.5	.5	.4
Charlottesville ..	.2	.2	.2	.2	.4	.5	*1.1*	*1.3*	.4	.4	.4

ered the continent from March 6th to 8th nor the deep depression in the Lake region on March 10th to 11th caused microseisms of remarkable extent. The higher values at Saskatooon may be influenced by the fact that a small instrument with low magnification is in use there and that the results change with the friction of the writing point on the smoked paper. As soon as the depression reached the coast, the intensity of the microseisms increased at all stations in the east and in the central part of North America. Though the storm traveled rather fast to the northeast, the stations in the southeast and central parts showed no decrease. So we see a very remarkable difference between the behavior of the microseisms in the two cases of storm, in the west and in the present case. In the first two cases the microseisms are more local. When the storm moves from the north to the south, the microseisms show a similar change. But in the case here discussed they changed in the same manner at all stations in the eastern half of the continent without being influenced by the position of the low pressure in regard to the station. Besides, the movements all were propagated to greater distances (compare Tucson and Saskatoon in the first cases, and St. Louis, Florissant, and Charlottesville in the present case). But we now find no great change of the microseisms in the west. At first glance these results may look somewhat strange, but we have found similar results in Europe. Storms near most coasts there, also, produce only local microseisms, but if there is high surf on the Scandinavian coast microseisms throughout Europe and in western Asia increase at once in the same ratio.

To get a view of the region where the storm is most active in causing microseisms, in Table VII the direction and velocity of wind are reproduced according to the United States Weather Bureau maps. The velocity is given in miles per hour. The velocity in meters per second is somewhat less than half these values. If we compare Table VII with Table VI, we see that strong winds in the middle east, even against the coast, have no effect at all. The large movements arise during the time when the storm blows against the steep rocky shores of Newfoundland and Canada. So we find the large microseisms over extended areas under exactly the same conditions as in Eurasia.

During this microseismic storm the periods of seismic waves did not change very much. A mean value of six seconds was again found at all stations. At Ottawa and Seven Falls only, the periods increased to seven and sometimes seven and one-half seconds during the storm. In general at the other stations values of six and one-half seconds were not exceeded. At Cambridge the period even decreased somewhat and waves with periods of four seconds were found during the storm. This may have had some local cause.

The most interesting interval which was investigated was that extending from March 24 to 28, 1930. Although Figure 1 shows four weather maps covering this time, a short description of the development of the depression during this interval may be given. On March 24th, at 8: 00 a.m., Eastern Standard Time, a large low-pressure area with a minimum of 29.6 inches covered the continent, with its center south of the Lake region. Another depression disappeared to the northeast during

TABLE VII

Direction and Velocity (Miles per Hour) of Wind Near the Atlantic Coast in March, 1930

	March 8, 8^h		March 9, 8^h		March 10, 8^h		March 11, 8^h	
Cape Race	(E)	16	(E)	*30*	(?)	*52*	(SW)	12
Father Point, Quebec	?		NE	*36*	SW	28	W	12
Eastport, Maine	E	20	...*		...*		...*	
Portland, Maine	NE	12	...*		...*		...*	
Boston, Massachusetts	NE	10	...*		...*		...*	
Nantucket, Massachusetts	E	*30*	W	12	W	12	S	10
Atlantic City, New Jersey	S	*22*	W	*22*	W	14	S	*20*
Hatteras, North Carolina	SW	12	W	24	...*		SW	10

* Less than ten miles per hour.

the day. The southern part is still visible on the northeast corner of the map. The first-mentioned depression moved northeastwardly during the following days. As shown in Figure 1, its central and largest part did not leave the continent. The center was situated on March 25th at 8:00 a.m. southeast of Chicago and northeast of St. Louis with a pressure less than 29.3 inches; at noon near Washington, D.C., with a pressure less than 29.2 inches; on March 26th, at 8:00 a.m., in the region of Ottawa with less than 29.0; on March 27th, at 8:00 a.m., north of Ottawa and northwest of Seven Falls with 29.1; and in the morning of the 28th near the mouth of the St. Lawrence River with somewhat over 29.4 inches, the gradients now decreasing rather fast.

The amplitudes of the microseisms and their periods are given in Figure 2, in the same units as shown before. The sudden increase in motion as well as in the periods is very striking. In this instance even the stations in the West showed a decided increase of amplitudes, which was recorded at exactly the same time as in the East. However, at Berkeley and Lick the amplitudes were so small that they could not be measured, but one must consider that these two stations at that time had no instrument with large magnification for long-period waves. The

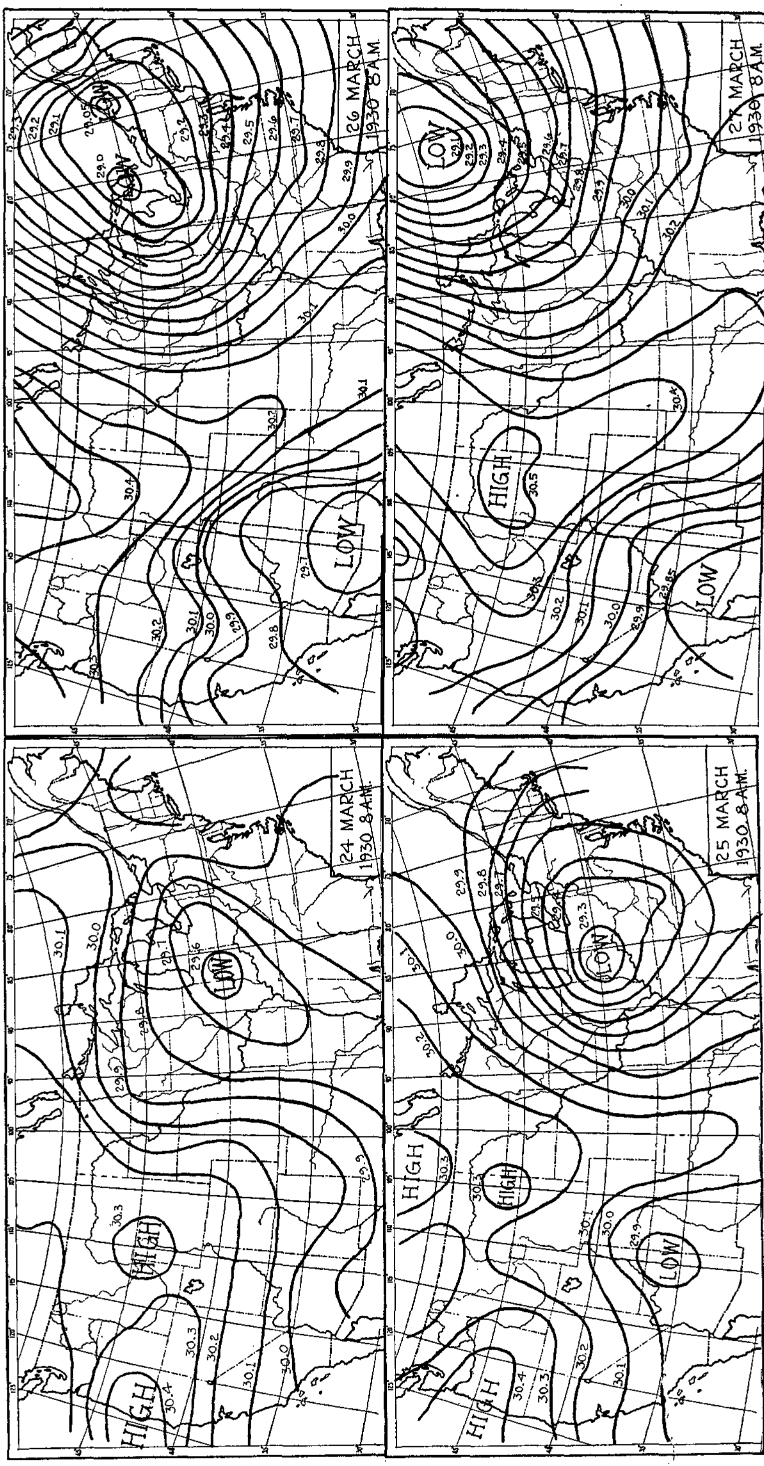

FIG. 1.—Weather Maps

increase of the periods in the early hours of the 26th was the same at all stations over the continent without relation to the absolute amplitudes at the different stations. This was the only case of all those considered in which the periods ranged between eight and nine seconds.

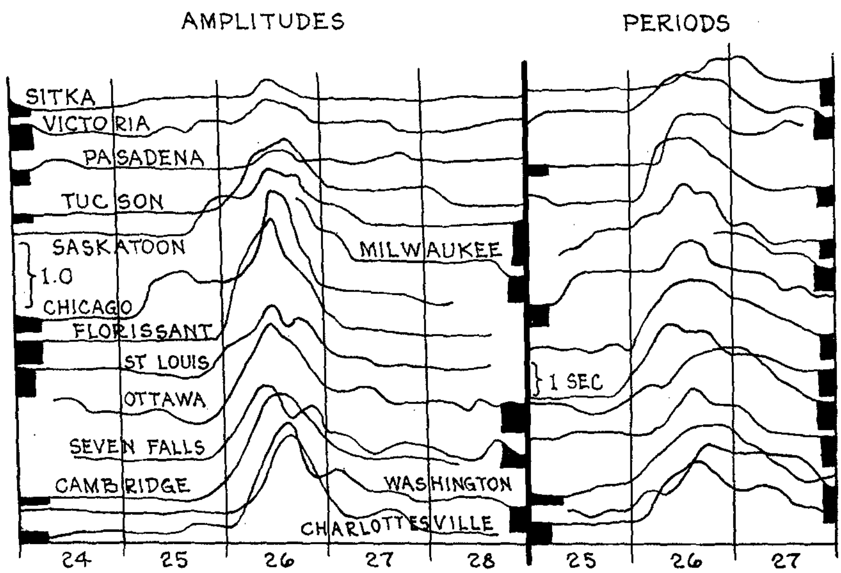

FIG. 2.—Amplitudes (units as in Table IV) of microseisms at different observatories from March 24, 0^h, to March 29, 0^h, 1930, Central Standard Time (left), and periods from March 25 to March 28, 0^h (right). The base line for the amplitudes is 0, for the periods 6 seconds. It is marked at one edge for every curve by the lower limit of the black space.

These values were found everywhere except at Pasadena and Sitka, where they were between seven and eight sconds. The decrease in the periods took place more slowly than the decrease of the amplitudes as Figure 2 shows.

Figure 3 (p. 14) exhibits a portion of the seismograms of March 26th as recorded at some stations. At Florissant the time marks are made every half minute, at the other stations every minute. The interval between two horizontal lines is nearly half an hour in the former case and at Washington also; but nearly an hour in the other cases. An earthquake which was recorded at all stations may serve as a time-mark for the different seismograms. The first motion occurred at about half past one

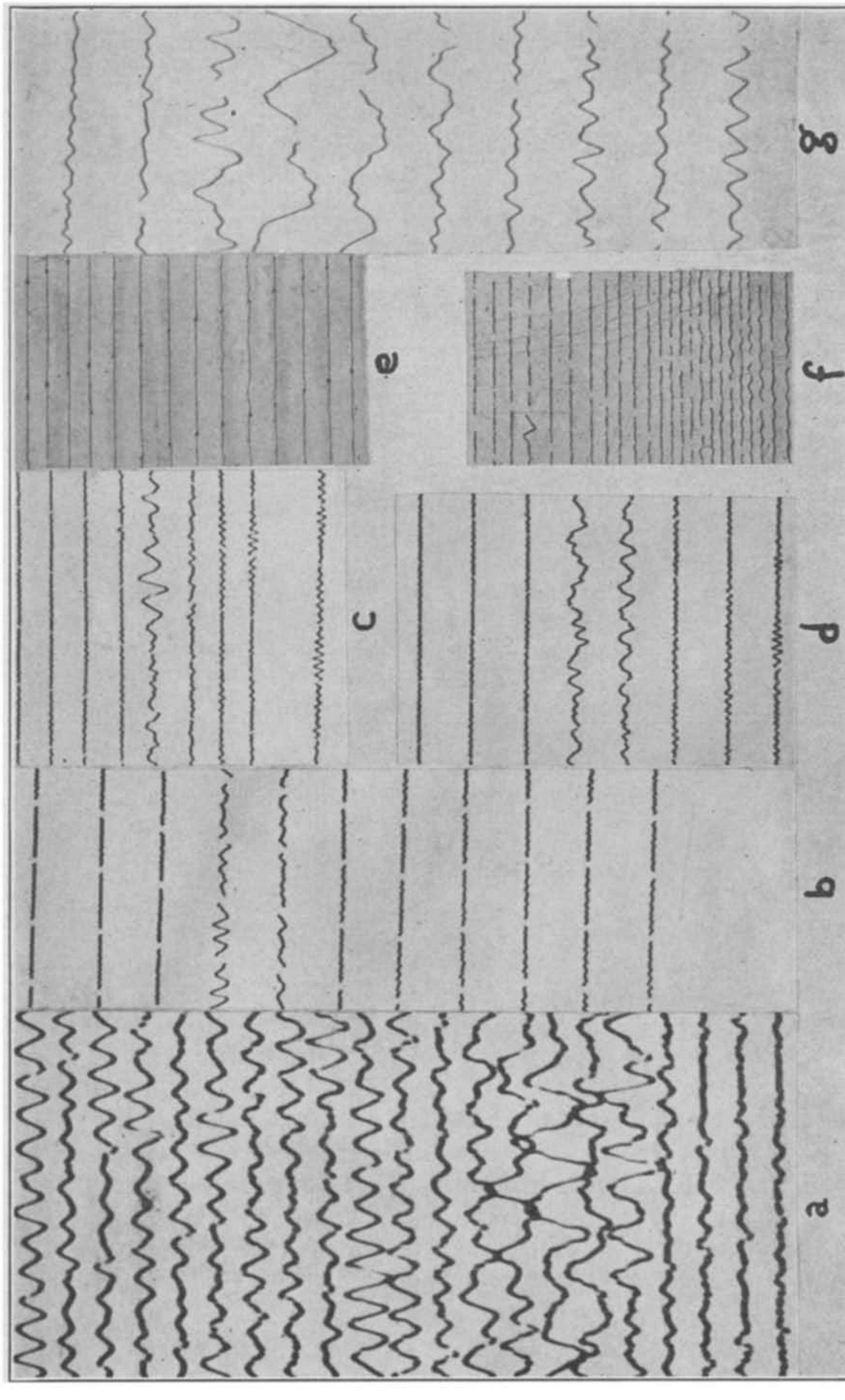

FIG. 3.—Microseisms and part of an earthquake March 26, 1930. *a*) Florissant, Galitzin pendulum, vertical. *b*) Victoria, B.C., Milne-Shaw, EW. *c*) Ottawa, Milne-Shaw, N.S. *d*) Cambridge, Milne-Shaw, N.S. *e*) Charlottesville, inverted pendulum, $V = 75$, N.S. *f*) Saskatoon, little Mainka, $V = 61$, N.S. (the earthquake is to be seen on the sixteenth line from the top). *g*) Washington, D.C., Galitzin pendulum, vertical. In figure *a*, the time runs from the bottom to the top; in all others, from the top to the bottom.

in the morning, Central Standard Time. It can be seen clearly that at all stations the microseisms increased very rapidly at about the time of the earthquake and more slowly during the following hours. The earthquake occurred probably in the Banda Sea (East Indies) and naturally had no connection with the microseisms.

In Table VIII the direction and velocity of the wind near the coast is given as well as it could be compiled from the Washington weather maps. It is very regrettable that no data for other hours could be supplied by the United States Weather Bureau.

TABLE VIII

DIRECTION AND VELOCITY OF WIND (MILES PER HOUR) NEAR THE ATLANTIC COAST IN MARCH, 1930

	March 24, 8^h		March 25, 8^h		March 26, 8^h		March 27, 8^h		March 28, 8^h	
Cape Race	(W)	12	*(W)*	*36*	?	20	(SE)	12	...*	
Father Point	W	28	...*		*(NE*	*48)*†	E	12	W	12
Eastport	W	10	...*		E	28	SW	14	SW	12
Portland	...*		...*		N	10	SW	10	...*	
Boston	...*		...*		...*		...*		...*	
Nantucket	...*		SE	14	SW	18	SW	*32*	W	20
Atlantic City	S	12	SE	24	SW	22	SW	24	SW	24
Hatteras	E	12	SW	10	W	30	SW	20	SW	20

* Less than ten miles per hour.
† Quebec; no report from Father Point.

By comparing the microseisms with the situation of the low-pressure area and the wind near the Atlantic Coast, we may see again very clearly that neither the pressure nor its change nor the wind in the Middle East or Southeast can have produced the motion. Microseisms of large amplitude were registered as soon as the low-pressure area caused strong winds and surf against the rocky coast of the Northeast.

In previous paragraphs we have chosen certain distributions of air-pressure and tried to find corresponding microseisms. Reversing the procedure, we may look for days with large microseisms and compare them with the distribution of air-pressure. The seismographic station at St. Louis University reported "Midnight to midnight strong microseisms January 29–30, 1930." A few stations therefore were requested to lend their seismograms for the dates January 28–31. Table IX (p. 16) gives the measured amplitudes, Table X (p. 17) winds near the coast. On January 28th a low-pressure area of 29.7 inches covered the northern Lake region. It moved to the northeast and was situated near the Gulf of

St. Lawrence in the morning of the 29th, with a pressure less than 29.45. A new depression appeared at the northwest corner of Florida with a pressuré less than 29.9. The first one moved toward Greenland during the following twenty-four hours; the second one was situated east of Hatteras in the morning of the 30th, with a pressure less than 29.7 inches. During the day it moved to the north very rapidly, joined another low-pressure area, which had been north of the Lake region during the day, réached the region east of Ottawa in the morning of the 31st (less than 29.8 inches), moved along the valley of the St. Lawrence River during the day, and reached the ocean during the following night. Two other areas of low pressure had moved toward the west coast of Alaska and northern Canada on January 30th and 31st. They had their steepest gradients on February 1st and 2nd. The minimum on this date was 28.6 inches, west of Sitka.

TABLE IX

RELATIVE AMPLITUDES OF MICROSEISMS, JANUARY 28 TO FEBRUARY 1, 1930

	28^d12^h	29^d0^h	29^d12^h	30^d0^h	30^d12^h	31^d0^h	31^d12^h	1^d0^h	1^d12^h	2^d0^h
Sitka	.3	.3	.2	0.2	0.4	0.2	0.3	0.4	0.4	*1.0*
Berkeley	.0	.0	.0	0.0	0.6	0.4	0.4	0.0	0.0	?
Pasadena	.2	.2	.2	0.3	0.3	0.7	0.4	0.3	0.3	0.4
Tucson	.2	.3	.4	0.5	0.7	*1.1*	0.9	0.8	0.6	0.8
Saskatoon	.3	.5	.5	0.7	*1.2*	*1.0*	*1.0*	*1.0*	0.8	*1.2*
Chicago	.5	.5	.5	0.5	0.9	*1.3*	0.6	0.6	0.6	0.6
Florissant	.3	.4	.4	0.5	*1.4*	*1.1*	0.6	?	?	?
St. Louis	.7	.7	.8	*1.2*	*2.2*	*1.4*	*1.2*	?	?	?
Ottawa	.7	.6	.7	0.7	*1.1*	*1.0*	*1.2*	*1.0*	0.8	0.8
Seven Falls	.8	.8	.8	0.8	*1.4*	*1.1*	*1.4*	*1.8*	*1.7*	*1.3*
Washington	.4	.8	.9	0.9	*2.5*	*3.1*	*1.6*	?	?	?
Charlottesville	.6	.6	.2	0.8	*1.6*	*1.8*	0.8	0.4	0.5	0.7

The general meteorological situation is rather similar to the situation in the preceding case, and the amplitudes of the microseisms change in a similar way. The most interesting difference is that in the early morning of January 30th the center of the depression was over the sea, but that the largest increase of microseisms occurred just when it moved back to the continent, and that the microseisms in general decreased when the depression reached the ocean again and then moved eastwardly.

Further, strong microseisms were observed at St. Louis on February 6–7, 9–10, and March 3–4, 1930. In all three cases low-pressure areas with steep gradients were situated near the mouth of the St. Lawrence River.

TABLE X

Direction and Velocity of Wind as in Table VIII from January 29 to February 1, 1930

	Jan. 29		Jan. 30		Jan. 31		Feb. 1	
Cape Race	?	16	?	*48*	?	*24*	(W)	*24*
Father Point	...*		...*		...*		...*	
Eastpoint	W	16	N	10	N	14	...*	
Portland	...*		...*		...*		...*	
Boston	W	12	...*		...*		...*	
Nantucket	NW	20	NE	12	N	14	W	16
Block Island	W	*32*	NE	*24*	N	10	W	18
Atlantic City	NW	20	NE	*36*	...*		...*	
Hatteras	NE	*32*	N	*32*	N	12	...*	
Charleston	NE	*22*	N	18	...*		...*	

* Less than ten miles per hour.

Before general conclusions are drawn we must give theoretical consideration to the origin of the microseisms and their energy.

Theory

As was pointed out in the introduction there are two different kinds of hypotheses regarding the origin of the microseisms. The one considers changes of pressure over the sea, due to slight changes in air pressure (Gherzi) or to sea-waves (Biot, Banerji), as the cause of the microseisms; the other one attributes the microseisms to the surf along steep, rocky coasts (Wiechert, Gutenberg). Now, it is very improbable that changes of pressure of any kind are propagated through the water to the bottom of the ocean, as the first hypothesis assumes. We know from the theory, for instance Lamb (10), that such disturbances decrease very rapidly with depth, if the wave-length is less than the depth of the sea; and we know on the other hand from the submarines that experience verifies this result. Banerji himself gives the principles of the theory. He assumes a gravitational wave of the form

$$A = a \sin (nx - pt) \tag{1}$$

in which $A =$ elevation, $a =$ amplitude, $n = 2\pi/L$, $L =$ wave-length, $p = 2\pi/T$, $T =$ period. If furthermore $d =$ depth of the sea, and

$$p^2 = gn \tanh nd \tag{2}$$

according to the usual theory, Banerji obtains the velocity potential

$$\phi = \frac{ag}{p} \frac{\cosh n\,(z+d)}{\cosh nd} \cos\,(nx - pt). \tag{3}$$

The hydrodynamic pressure is

$$\frac{P}{\varrho} = \frac{\partial\phi}{\partial t} - gz - \left[\left(\frac{\partial\phi}{\partial x}\right)^2 + \left(\frac{\partial\phi}{\partial z}\right)^2\right] + \text{const.} \tag{4}$$

The changes of pressure diminish very rapidly with depth z: At the bottom of the sea, putting $z = -d$, in (3), he obtains

$$\frac{P}{\varrho} = \frac{gA}{p \cosh nd} + \text{const.} \tag{5}$$

which means that the pressure is nearly constant. In the case of Gerstner waves (trochoidal waves) which have not been considered by Banerji but which approximate the actual sea-waves rather well, the amplitude of the change of pressure at the depth of $-h$ in deep water (d again large in comparison with L) is given by

$$\Delta P_z = \pi\varrho\, n^2 LAe^{-\frac{2\pi h}{L}} \tag{6}$$

If we put $L = 100$ meters we find at a depth of (7)

	0 m	50 m	100 m	500 m
$\Delta P_z : \Delta P_0$	1	1:14	1:200	$1:3\times10^{11}$.

We can now follow Banerji's paper. He states: At the bottom of the sea "the pressure disturbance therefore becomes negligible except when the waves advance over shallow water. This would then suggest that there is no stress disturbance at the bottom of the deep sea, and the microseisms can be developed only when the gravity waves advance over shallow water. But we have already pointed out that microseisms begin to make their appearance long before the arrival of the monsoon current . . . . with rough seas. Storms also invariably give rise to pronounced microseisms when they are" still far from the station.

Up to this point Banerji is right without any doubt, and the consequence therefore must be: The gravity waves (and other changes with similar or shorter periods taking place at the surface of the ocean) cannot be the cause of the microseisms. We must consider another factor, for example the surf, which also acts at some distance from the stations due to rough seas. On the other hand, we must consider that we can have strong microseisms when the low-pressure area is near the coast but still on the continent. But Banerji thinks that the equations do not hold in the case of such depths, that they are applicable only to the superficial layer. "The pressure disturbance at the bed of the sea can be obtained in two stages. Assume that the motion due to the surface disturbance has become negligible at the depth $z = -h$, in which h is only a small fraction of d. Then if P_1 is the pressure disturbance at this depth, equation (3) gives" according to Banerji

$$P_1 = g\varrho \ (h + A) \tag{I}$$

But if d is large, according to Banerji in (3)

$$\frac{\cosh n \ (z + d)}{\cosh nd} \tag{II}$$

is approximately equal to unity within the region in which Equation 3 may be considered to remain valid, and 3 therefore reduces to

$$\phi = \frac{Ag}{p} \cos \ (nx - pt). \tag{III}$$

"The pressure P_2 due to the column of fluid between this level ($z = -h$) and the bed of the sea ($z = -d$) is simply $g\varrho \ (d - h)$. The total pressure at the bed of the sea is therefore $g\varrho \ (d + A)$. In other words: the stress over each element of area of the bed is equal to the weight of the superincumbent fluid at any instant."

The reason Banerji now obtains a result so different from the one found before, is that Equation III holds only if z is very small. We cannot consider this in our calculations. The true forms of Equations II and III are

$$\frac{\cosh n \ (z + d)}{\cosh nd} = e^{nz} = e^{\frac{2\pi z}{L}} \tag{8}$$

$$\phi = \frac{Ag}{p} \ e^{nz} \cos \ (nx - pt) \tag{9}$$

If we now use Equation 9 to a depth $z = -h$, where the surface disturbance has become negligible, we find, as in the case of Equation 6 the coefficient $e^{\frac{-2\pi h}{L}}$. This neglected coefficient e^{nz} becomes very small with increasing depth and we see again that at the depth h the change of pressure due to the gravitational wave has become just as negligible as the disturbance. The periodical disturbances at the surface of the sea can produce stresses at the bottom of the sea only in shallow water, that is if the wave-length of the disturbance is markedly larger than the depth of the sea.

Now let us raise the question whether surf can be the cause of microseisms. Surf is caused by sea-waves and its energy depends upon the kinetic energy of these waves and also upon the direction of the wind, on shore or off shore. More energy will be transferred to the rock when the wind blows against the shore. We will not take this fact into consideration, as it is very difficult to make any calculations regarding it. Let us only assume that a fraction f of the energy of the sea-waves traveling with their normal velocity is transferred to the coast, where f will be less than unity.

The kinetic energy of a wave depends upon the form of the wave. But as we can only calculate the order of the quantities used in our problem, we will assume that we have Gerstner waves (trochoidal waves). In this case the kinetic energy E per second of a wave with the length L of the height H, and of the period T is given by

$$E = \frac{gLH^2}{16T} \tag{10}$$

If we now suppose that the length of the coast, against which the waves are driven by wind, is l, the whole energy of such a wave front traveling toward the coast is given by El. The waves are thrown against the coast, but the whole of the energy is not transferred to the coast. A part of it is lost by friction between the water particles or between water and rock or sand. The flatter the coast the less energy is transferred to it. In the case of very flat, sandy shores nearly all the energy is lost by friction. Therefore we do not get large microseisms even if a heavy storm blows against a shore of this kind. We see that the energy which strikes the coast is given by

$$E = f\,\frac{gLH^2l}{16T} \tag{11}$$

in which f is a factor, caused by the friction of the waves, which is less than unity, but a rather large fraction in the case of steep coasts of solid rock.

To obtain an estimate of the order of E we use the following values: $L = 100$ m $= 10^4$ cm; $H = 5$ m $= 5.10^2$ cm; $T = 8$ seconds; $l = 500$ km $= 5.10^7$ cm. With these values, which are fairly probable, we find $E = 10^{18}\,f$ ergs per second, which means that the energy transferred to the coast would be of the order of 10^{17} ergs per second. If we compare this result with the energy of earthquakes, which is of the order of 10^{20} to 10^{24} ergs in normal cases, we see that it is less. But we must take into consideration that in the case of earthquakes the energy is liberated but once, while in our case this energy is produced every second. For this reason and in view of the fact that the amplitudes of these waves are proportional to the square root of the energy, it may safely be concluded that the microseisms are actually caused by the surf.

To find the order of the amplitudes of the waves produced by the energy found, we use a formula of Jeffreys (11). If $d =$ density, $R =$ radius of the earth, $D =$ distance from the source, $a =$ amplitude, and $T =$ period of Rayleigh waves at this distance, $C =$ velocity of such waves, $L =$ wave-length, we get as a first approximation the following equation:

$$E = 8\pi^3 d\, R \sin D \int \frac{7a^2LC}{2\pi T^2}\, dt \qquad (12)$$

In our case we will assume that all these quantities are constants, and further that the microseisms consist of Rayleigh waves and that the energy acting during the time t causes the amplitudes a during the same time t. So in putting $t = 1$ second we obtain the following equation, which can only give a very rough approximation of the order of a,

$$a^2 = \frac{TE}{5.10^{11}C^2 \sin D} \qquad (13)$$

We have found that E is of the order of 10^{17} ergs per second. If besides this we use the following rather well-known values: $T = 7$ sec., $C = 3$ km/sec., we find that at a distance of $30° = 2{,}700$ km from the source, a must be of the order of 50 μ. This value is higher than the values observed generally in the case of large microseisms, but we cannot expect to find more than the approximate order of the amplitudes. At any rate, the preceding calculations have shown that the surf against steep, rocky coasts in the case of rough seas must produce very large microseisms over entire continents, as we actually observe.

Summary

The microseisms in North America show in general the same peculiarities that they show in other regions, especially in Europe. When there is a storm near the coast we find short waves which are more or less irregular and which have periods between one half and several seconds. At more distant stations the periods are in general between four and nine seconds.

The amplitudes are influenced by the subsoil. The stations at

Milwaukee and Chicago (United States Coast and Geodetic Survey) especially show larger amplitudes than other stations. These larger movements may be caused by the moist nature of the soil near Lake Michigan. The smallest microseisms were found at Tucson. The subsoil there is sand or loose gravel.

To eliminate the effect of the subsoil and of errors in the magnification of the instruments, the mean maximum of four time intervals was taken as the unit at every station. Amplitudes measured in these units are called "relative amplitudes." If one draws maps with these relative amplitudes at the different stations, one finds that the lowest values cover one region and the highest values another. Figure 4 shows the values and lines of equal relative amplitudes on four different dates. The lines could be drawn only very roughly as the values are influenced by various errors and as only a very few points could be used. Such maps were drawn for all cases and hours discussed in this paper.

The distribution of the areas with large microseisms depends upon the position of the low-pressure area in the following manner: Low-pressure areas approaching the west coast of North America cause an increase in microseisms near the region where they approach the coast. These movements are not propagated very far along the coast nor perpendicular to it. At the stations in the center of the continent there is sometimes a slight increase of motion. Storms and low-pressure areas over the central parts of the continent do not cause microseisms at all. Also when they reach the coast of the Atlantic in the southern or middle east no microseisms or only local motions arise. But as soon as they approach this coast in the north, microseisms increase over the whole continent, especially if the depressions have steep gradients and cause storms against the coasts of Newfoundland and Canada.

So we find that, just as in Europe, surf due to storm against steep, rocky coasts is the cause of the microseisms with periods of four to nine seconds. Also, just as in Eurasia, where the movements are propagated best if the Scandinavian Shield is shaken, we find the largest area with large microseisms if the Canadian Shield is shaken by the storm-surf. In Europe the young mountains in the south cause rather rapid decrease in the motion. In western America the higher folded mountains nearly prevent the propagation of the movements by reflecting and refracting a large part of the energy.

Observations show that neither the air-pressure, nor its change, nor storm can be the cause of the microseisms. The result of the calculations is that no possible disturbance near the surface of the ocean can be

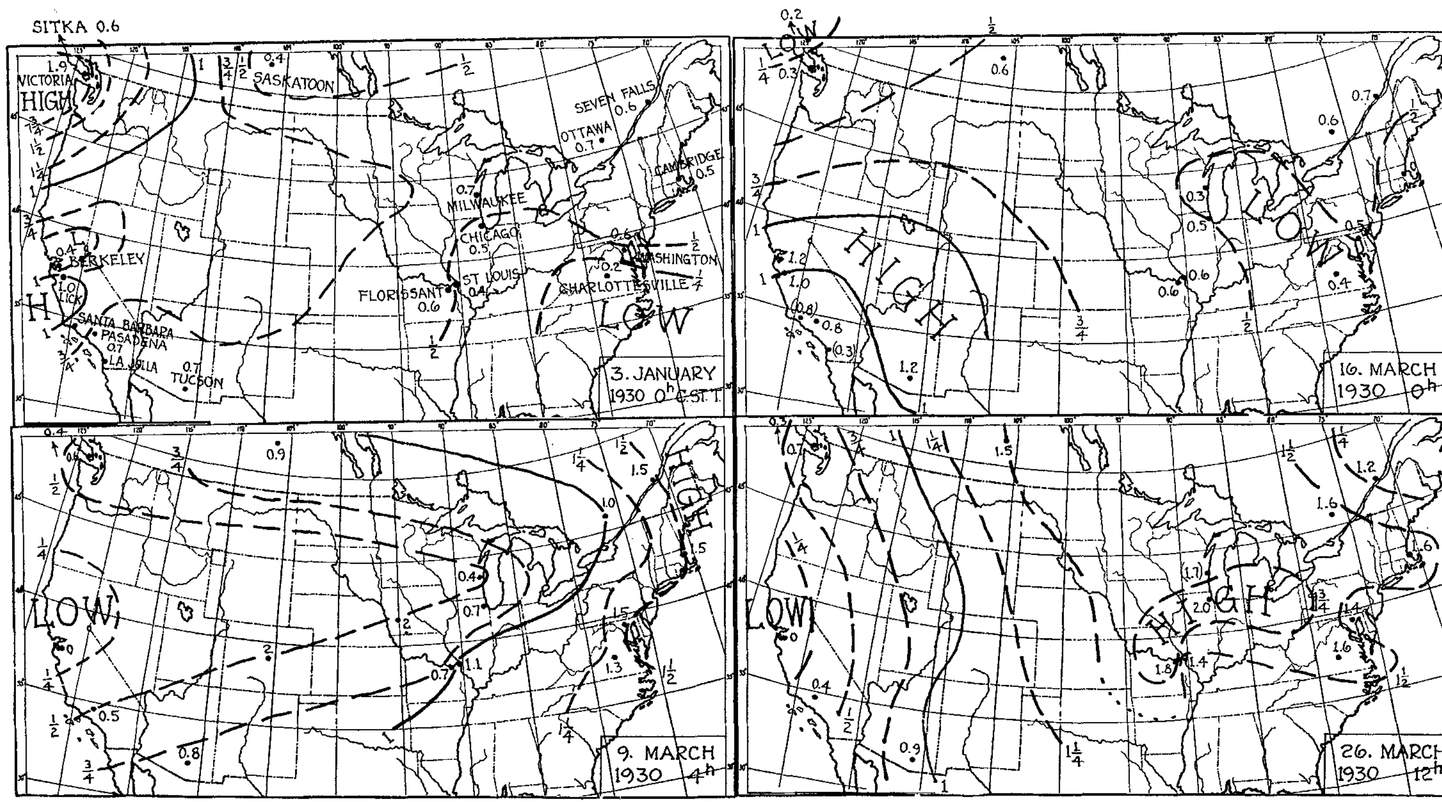

FIG. 4.—Amplitudes of microseisms and lines of equal amplitudes (units as in Table IV) at four different instants. The meteorological situations are given on pp. 6–15.

propagated through the water to the bottom, but that the energy of the waves transferred by the surf to the coast is large enough to cause the movements. Therefore, Wiechert's hypothesis that the surf produced by storm blowing against a steep rocky coast is the cause, will hold over the whole earth. Special conditions, the areas permitting good propagation and mountain ranges hindering the movements, must be investigated in special studies. In addition to its general views, this paper constitutes the first study of this kind in the case of North America.

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