ON A STUDY OF MICROSEISMS RECORDED AT SITKA, ALASKA, DURING THE PERIOD FROM JANUARY 1, 1929, TO DECEMBER 31, 1931, INCLUSIVE*

By Donald C. Bradford

As Gutenberg[1] has said: "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.' "

We may segregate roughly into three groups the various theories which have been formulated with regard to the causes of the several types of microseisms which have been recognized. The oldest and best known of these is the surf theory, first suggested by Wiechert and defended by his pupil Gutenberg. In essence, this theory holds that strong surf, while beating against a steep rocky coast, may propagate motion in the form of microseisms over an entire continent. This contention will be discussed in later pages of this paper. The second theory is that of Banerji,[2] who suggests that wave motion on the sea surface is propagated to the sea floor as a time variation of load. The validity of this hypothesis is questioned by many physicists. The only evidence favoring the Banerji theory is the fact that microseisms often form almost simultaneously with the beginning of disturbed weather far at sea, long before the advent of strong surf on the shores of India. The third theory, which, to distinguish it from the other theories already named, the writer will call the Gherzi theory, deals with the idea of an oscillating atmosphere which will in turn affect the ground, producing oscillatory motion in the upper layers of the earth's crust.

The main points of these theories will be discussed at some length, particularly the first and last.

Proposed New Classification of Oscillations Recorded by Seismographs Exclusive of Earthquakes

Class I. *Produced by agents affecting only the instrument.*

A. Oscillation of air in the instrument room caused by the turbulent motion of ventilating and eddy currents.

B. Irregular displacement of the recording instrument caused by insect movements.

C. Other causes.

* Manuscript received June 10, 1935.

[1] B. Gutenberg, "Microseisms in North America," *Bull. Seism. Soc. Am.*, 21:1 (1931).

[2] S. K. Banerji, "Microseisms Associated with Disturbed Weather in the Indian Seas," *Phil. Trans., Roy. Soc. London,* 229:287-328 (1930).

Class II. *Produced by agents affecting the immediate surroundings of the instrument.*

A. Oscillation of the pier with temperature changes.
B. Oscillation of the instrument housing and immediate vicinity with differential heating and cooling.
C. Effect of the wind on the instrument housing.
D. Other causes.

Class III. *Produced by agents actually causing ground motion.*

Type I. Short-period local disturbances, less than two seconds.
a) From waterfalls.
b) From near-by machinery.
c) From traffic and railroads.
d) From volcanic eruptions.
e) From other causes.

Type II. Disturbances of period between two and seven seconds.
a) From surf.
b) From barometric disturbances.
c) From other causes.

Type III. Motion of period greater than seven seconds.
a) From the effect of freezing in the upper layers.
b) From wind friction on the ground surface.
c) From other causes.

Much work has been done on the various classes and subclasses outlined in the foregoing classification. Likewise, much work remains to be done before the causes peculiar to each type are conclusively named. As Type II, Class III, contains what may be called the "ordinary" microseisms, and as there would not be room in a paper of this size to consider all types exhaustively, I shall give over the lion's share of my remarks to what has commonly been called "ground unrest," or "Bodenunruhe," as indicated by microseisms which possess periods of from two to seven seconds. Let us consider first the surf theory.

The Surf Theory

The theory of Wiechert, that the pounding of surf on steep rocky coasts is the cause of microseisms over all Europe, has been for many years the prevalent theory of the cause of this phenomenon. Wiechert's pupil, Gutenberg, has since been the most prominent exponent of this theory. Through the use of mathematical correlations, he has attempted to prove that the continental trembling over most of Europe and Asia as far east as Irkutsk is caused by the action of surf on the steep rocky coasts of Norway. He has also worked on the correlation of microseismic motion in North America with the action of surf on the various coasts.

One of the main objections to this theory is that at most points in North America the coasts are not steep, but are dominantly flat. The surf, therefore, instead of breaking with great force on these flat shores, would lose most of its energy in friction on the sands and rocks. Furthermore, it must be recognized that storm surf is only one of several results of the generation and movement of a severe cyclonic depression.

Because many able mathematical analyses of the wave form of surf, and of the energy content thereof, have been made, the writer will not enter into this phase here. Gutenberg[3] has dealt with the energy resulting from impact of waves of trochoidal form as expressed by the relationship

$$E = \frac{gH^2Llnf}{16T} \tag{1}$$

where g is the value of gravity, H is the height of the wave, L the length of the wave, l the length of coast over which the wave is striking, T the period of the wave, and f the coefficient of friction between the water and beach materials. If we substitute for the factors given above the following,

$$\begin{aligned} H &= 5 \text{ m.} = 5 \times 10^2 \text{ cm.} \\ T &= 8 \text{ sec.} \\ l &= 500 \text{ km.} = 5 \times 10^7 \text{ cm.} \\ L &= 100 \text{ m.} = 10^4 \text{ cm.} \\ g &= 980 \text{ cm/sec.}^2 \\ n &= 1 \end{aligned}$$

we find $E = 10^{18}$ (f) ergs per second. Gutenberg assigns a value of 0.1 to f, which would mean that the energy transferred to the coast would be of the order of 10^{17} ergs per second. The energy of the normal earthquake is from 10^{20} to 10^{24} ergs. Therefore, we see that the energy postulated for microseisms resulting from wave impact is much less. Gutenberg says that the energy of impact is being liberated continuously, and will give rise to the observed unrest.

It will be seen that the values assigned to the factors of Gutenberg given above are for an ideal occurrence. From the writer's study of the Sitka microseisms, it seems reasonable that the length of coastline affected by the surf may be reduced. This is in view of the fact that the well-known counterclockwise motion of the cyclonic vortex will give a varying direction of the wave incidence with increasing length of coastline.

We must also take into consideration that almost all steep coasts possess this steepness through sinking in relation to the sea level. Therefore, they are very irregular, with alternate sharp peninsulas and deep embayments. Some

[3] B. Gutenberg, *op. cit.*, p. 20.

may argue that wave refraction will ensure the normal incidence of an advancing wave front. The writer will here quote Johnson[4]:

Waves do not always break parallel with the shore. In the first place, no wave can be refracted with sufficient abruptness to render its crest parallel to the sharp and complex irregularities of some shores. In the second place, the water is very deep close to some shores, and wave refraction does not begin to take place until the wave has practically reached the headlands. The wave then breaks against the projecting points of the coast first, and its remaining portions, being imperfectly refracted, sweep upon the shore from the headlands inward at an oblique angle. Furthermore "forced waves" or those which are still being driven toward shore by the wind which formed them, are not so readily refracted as "free waves" which have passed beyond the limits of the storm. It is for this reason that storm waves are more apt to strike the shore at an oblique angle than are the groundswells which arrive during calm weather.

We may liken this effect to a decrease in a factor n, which will represent a lessening of energy imparted to the coast through variation from normal incidence of the wave.

Instead of evaluating the factor f as 0.1, let us assign to it a value of 0.001, for a coast which is of dominantly gentle slope; likewise we will give to the factor n a value of 0.8, which will correspond to an average variation from normal incidence of 30°. The factors used in the following solution will be:

$$\begin{aligned}
H &= 5 \text{ m.} = 5\times10^2 \text{ cm.}\\
T &= 8 \text{ sec.}\\
l &= 200 \text{ km.} = 2\times10^7 \text{ cm.}\\
L &= 100 \text{ m.} = 10{,}000 \text{ cm.}\\
f &= 10^{-3}\\
n &= 8\times10^{-1}\\
g &= 980 \text{ cm/sec.}^2
\end{aligned}$$

The resulting energy will then be found to be of the order of 3×10^{14} ergs per second. This is quite different from the 10^{17} ergs per second which was postulated by Gutenberg.

In an attempt to obtain by very rough methods the order of displacement of the ground resulting from the beating of surf on the coast for a distance of 30° from the source, Gutenberg used the following equation:

$$A^2 = \frac{TE}{(5\times10^{11})\,9\sin D} \tag{2}$$

where T equals the period of the microseismic wave at a distance of 30°, E is the energy term found in (1), 9 is the velocity squared of the Rayleigh wave, and D is the distance from the source in degrees.

[4] D. W. Johnson, *Shore Processes and Shoreline Development* (Philadelphia, John Wiley & Sons; 1919), p. 76.

Where Gutenberg used the value 10^{17} ergs per second, we will use 3×10^{14} ergs per second, and where he assumed T as equal to 7 seconds, we will use the value most often observed at Saint Louis, namely, 5 seconds. For the solution of this equation for $D = 30°$, so that we may compare directly with Gutenberg, we find $A = 0.316\mu$. This differs radically from the value obtained by Gutenberg for the same distance, 50μ. Thus we see that microseisms supposedly generated by surf could not be distinguished, at a distance, from microseisms which are often much larger and generated by other agencies.

In the statistical study of semidaily data on the size of microseisms, the strength of the surf, the strength of the wind, and the local barometric pressure readings, taken at Sitka, Alaska, during the period from January, 1929, to December, 1931, inclusive, the writer has found the correlation coefficient between microseisms and surf to be only of the order of 0.27. It will be remembered that Sitka is situated only a short distance from the coastline proper, and that the coast there is rugged. Furthermore, the Bering Sea is the scene of many severe storms, to such a degree that it has often been called the "Mother of Storms." Therefore, the writer places considerable weight on the data as found at this place.

In table 1 (p. 328) may be seen a table of corresponding values of the strength of the surf at Sitka and the intensity of microseismic activity, for different times of maximum activity of both.

From the data shown in table 1 it is easily seen that no direct correlation exists between the strength of the surf at Sitka and the simultaneous microseismic displacement. From this fact, and from foregoing arguments, it is apparent that surf cannot be postulated as either an exclusive cause or an important cause of ground unrest. Though it possibly may be a local cause, there must be other agents at work to produce motion great enough to be propagated over an entire continent, if indeed microseisms are transmitted that far.

The writer agrees with Lee[5] in the following statement concerning Gutenberg's theory,

> . . . No exact explanation of how the surf sets the ground in oscillation is given, but presumably Gutenberg envisages each breaker as a tiny earthquake generating surface waves. A difficulty at once confronts such an hypothesis, for the impacts of the waves would not occur simultaneously along the whole coastline affected, and consequently the agreement between the periods of the microseisms and of the sea waves is not explained.

Again, as Gherzi says:[6]

> . . . Rough sea is experienced with monsoon weather and with cyclone weather; the microseisms of both weather regimes are different. Then we draw the conclusion that the breaking of the surf does not explain this twofold aspect of the earth's vibrations and the

[5] A. W. Lee, "A Worldwide Survey of Microseismic Disturbances Recorded During January, 1930, "Air Ministry, Meterological Office, London, *Geophysical Memoirs*, VII:22 (1934).

[6] E. Gherzi, "Microseisms Associated with Storms," *Beitr. z. Geophysik*, Bd. 25, p. 146 (1930).

characteristic groups and the universally observed constant aspect of the period, four to six seconds. Once more, although Dr. Gutenberg gives very long analysis and very interesting, concerning the value of the earth's displacements, this we think is not the question to be solved.

TABLE 1

COMPARISON OF STRENGTH OF SURF AND OF MICROSEISMS AT SITKA

1929	1929	1930	1930	1930	1931	1931	1931
$S - U$	$S - U$	$S - U$	$S - U$	$S - U$	$S - U$	$S - U$	$S - U$
3 – 3	2 – 4	0 – 4	1 – 4	0 – 3	0 – 2	3 – 4	2 – 3
1 – 2	4 – 3*	1 – 3	2 – 4	1 – 2	0 – 3	1 – 3	2 – 4
2 – 3	1 – 4	2 – 4	2 – 2	2 – 4	1 – 3	2 – 1*	2 – 1*
2 – 4	3 – 4	1 – 4	1 – 3	2 – 4	1 – 3	2 – 2	2 – 4
1 – 3	2 – 4	0 – 4	0 – 3	1 – 2	2 – 3	2 – 4	3 – 4
1 – 4	0 – 4	2 – 4	0 – 2	1 – 4	2 – 4	0 – 3	1 – 3
1 – 4		0 – 4	3 – 1*		2 – 3	2 – 3	2 – 4
2 – 4		1 – 4	1 – 4		2 – 3	2 – 4	2 – 3
3 – 4		0 – 4	1 – 2		2 – 2	1 – 3	0 – 3
3 – 4		1 – 2	1 – 3		2 – 3	0 – 2	0 – 3
3 – 4		1 – 4	0 – 1		0 – 3	0 – 2	0 – 3
2 – 4		1 – 4	0 – 1		1 – 2	0 – 2	0 – 2
3 – 3		2 – 4	0 – 4		2 – 3	0 – 1	0 – 2
3 – 4		2 – 2	0 – 3		2 – 4	0 – 3	0 – 2
2 – 3		2 – 4	1 – 3		2 – 4	0 – 2	0 – 1

* Occurrences in which comparative strength of local surf exceeds microseismic activity.

S indicates surf; U indicates microseismic unrest. The scale used in evaluating the data of table 1 is as follows: Surf: 0 to 4; gradational from zero to the heaviest observed. Proportional intensity.

Unrest: 0, none whatever; 1, very light; 2, moderate continuous or few heavy microseisms; 3, continuous heavy or few extremely heavy recorded continuously; 4, very heavy, continuous.

(A microseismic strength of 4 corresponds to a ground displacement of about 8μ; 3, approximately 6μ; and so proportionally to 0.)

THE BANERJI THEORY

Rather than consider the actual breaking of surf as the cause of ground unrest, Banerji has extended the idea of the propagation of wave motion on the surface of the sea to the sea floor as a time variation of load. The validity of this hypothesis is questioned by many physicists. The evidence in favor of the theory is the following: Microseisms of a particular type form almost simultaneously with the beginning of disturbed weather far at sea, long before the advent of surf on the shores of India. The unrest often increases sharply with the approach of the storm toward the coast. For the stations situated near the coast, there may be an added effect caused by the surf. In a graph, Banerji (*op. cit.*, p. 296) shows the increase of intensity of microseismic motion as two different storms approached the Indian coastline, crossed it, dissolved, and ceased to affect the ground. It is notable that in the larger of the two storms the maximum ground motion occurred approximately nine hours before the storm crossed the coast. In the smaller storm the interval was not so great, but it must also be seen that the distance from the storm to the station was much greater and therefore the observable effects not so clear.

Banerji also brings out that if water waves of different periods exist simultaneously in time and space, superposition will occur. This superposition may induce a similar superposition of microseisms. Microseismic superposition does take place, as may be seen on the records from any seismograph of magnification greater than 200.

For discussions on the Banerji theory, the reader is referred to Gutenberg[7] and to Whipple.[8]

A time interval between an increase of microseismic motion and an increase of surf strength at Sitka was also noted. In the study of the Sitka data it was found that microseisms often begin as long as twelve hours before there is a sign of increase of surf activity. If we assume that Banerji's hypothesis is correct, we may make a few sample calculations.

If a storm is generated some 500 kilometers off the southern Alaskan coast, as often happens, it will take 167 seconds for microseisms in the form of a Rayleigh wave to reach the seismograph at Sitka. Simultaneously, it would take a water wave of length 300 feet, and with a velocity of 26.6 miles per hour, approximately 11.7 hours to reach the coast at the Observatory. Therefore we may neglect the travel time of the elastic wave, and assume the entire time interval to be the difference in arrival time between the elastic wave and the water wave. As has been said before, this interval is often observed at Sitka.

With reference to the work of Linke,[9] it may be said that it must be apparent that surf should affect islands more than continents. The smaller the island the greater should be the effect observed. With decreasing size, the length of coastline of an island increases in proportion to the area roughly as in the relationship

$$\frac{2\pi r}{\pi r^2} \tag{3}$$

On islands with submerged shelves of small extent and submerging at a large angle the effect of the surf would probably be more pronounced. With increasing steepness, the island will approach the form of a pillar which will show the effect of surf, seasonal changes in ocean currents, and other such phenomena. Therefore, the relationship of island microseismic activity to the various causes is not comparable to that observed on the continents.

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[7] B. Gutenberg, *op. cit.*, p. 17.

[8] F. J. W. Whipple, "Notes on Mr. A. W. Lee's Investigation 'A Worldwide Survey of the Microseismic Disturbances Recorded During the Month of January, 1930,' " *Publications du Bureau Central*, Union Géodésique et Géophysique Internationale, Association de Seismologie, Sér. A, No. 10, pp. 127-135 (1934).

[9] F. Linke, "Die Brandungsbewegungen des Erdbodens und ein Versuch ihrer Verwendung in der Praktischen Meteorologie," *Abh. der K. Ges. der Wiss. zu Göttingen*, N. F., II; *Ergebnisse der Arbeiten des Samoa-Observatoriums*, III (Berlin, 1903).

Repetti[10] has worked on the possibilities of predicting weather from the nature of the microseisms. He has found that there are certain occurrences of activity which cannot be explained on the basis of the surf theory. In these it was found that the barometric oscillations of the center of cyclones passing over the island of Luzon were the causative factor. It will be remembered that Luzon is the largest of the Philippine Archipelago. Repetti (*op. cit.*, p. 269) makes the statement:

> Many typhoons approach the Philippine Islands from the east and curve northward without actually touching the archipelago. Such typhoons do not normally give rise to microseisms until the center of the disturbance has reached such a position to the northeast of Manila that its southwest wind is felt on the west coast of Luzon. In these cases the microseisms become conspicuous three or four hours before the wind becomes well established at Manila, which is about thirty miles from the open sea.

It is quite easily to be seen that if the wind has not attained the velocity of 25 to 30 miles per hour, no appreciable surf will be generated. Manila is thirty miles from the open sea; yet the wind, which would take an hour to reach there from the open sea, does not reach Manila until three or four hours after the microseisms have become conspicuous. In other words, the surf has not increased until two or three hours after the beginning of the microseismic storm. Therefore, there must be some other method of propagation of energy to the upper layers of the earth's crust which will communicate the unrest to the station at Manila. This leads us directly to a discussion of the possibilities of a connection between atmospheric instability and microseismic phenomena. However, before a connection can be established, we must first investigate the existence of atmospheric oscillations.

The Gherzi Theory

In 1874, Rossi[11] directed attention to the possibility of a connection between microseismic motion and variations in barometric pressure. He stated that no marked barometric depression had occurred in the three previous years without having been immediately preceded, accompanied, or followed, by marked microseismic motion. He called these effects "baro-seismic."

Rossi thus expressed the fundamental idea with which the present writer is here concerned. Since that time, barometric changes have often been thought to be intimately connected with the source of microseismic motion, but no conclusive proof has ever been found.

It is well to enlarge on the theme of oscillatory and other atmospheric disturbances. The following is a classification adopted by the writer for the purposes of this paper:

[10] W. C. Repetti, "Preliminary Investigation of Microseisms in Manila," *Beitr. z. Geophysik*, Bd. 40, Heft 2/3, pp. 268-271 (1933).

[11] M. S. de Rossi, *Bull. del Vulcanismo Italiano*, I (1874).

Classification of Barometric Disturbances

Class I. The development of gradients

Class II. Nonperiodic pressure oscillations

Class III. Periodic pressure oscillations

- A. Regular
  - Type I. Tidal effects
  - (Under this head are included the points taken up by Bartels.[12])
  - Type II. Adiabatic effects
- B. Accidental
  - Type I. Action of tropical cyclones
  - Type II. Action of "extratropical" cyclones[13]
  - Type III. Turbulence from wind[14]

The Possibility of Microseisms Resulting From the Development of Gradients

It is probable that the structure of a heavy gradient is not essentially oscillatory, but the idea that a heavy gradient is capable of deforming the ground and is somehow able to produce microseisms has so often been suggested that it is impossible to overlook it here. The importance of this type of atmospheric configuration in the literature on the formation of microseisms is probably ascribable to the simultaneity of its occurrence with that of severe cyclonic depressions, and consequently with that of many marked microseismic storms. Though a heavy gradient assists in the deformation of the ground, it is difficult to understand how oscillatory motion of the upper crust would result.

Klotz[15] noted that microseisms recorded at Ottawa almost always corresponded in time to marked gradients to the east of Ottawa, over the Gulf of Saint Lawrence. However, when a low of even very steep gradient was to the west of Ottawa, over the Great Lakes, microseisms were generally very weak. This seeming locational preference for microseisms from this source nullified the use of microseisms in weather forecasting and precluded any positive results from studies of the relationship of microseisms and heavy gradients.

Omori[16] found that for a gradient of 10 mm. in 220 km. there was a simultaneous tilting of the ground equal to 3.5″. As this low was to the eastward of Tokyo, we should suppose that the pendulum would have shown a tilt to the west, but on the contrary it swung to the east. On another occasion this same

[12] J. Bartels, "Tides in the Atmosphere," *Scientific Monthly*, 35:110-130 (1932).

[13] Gherzi's nomenclature.

[14] This source of disturbance will be considered in the section on microseisms from wind.

[15] O. Klotz, "Microseisms," *Jour. Roy. Astron. Soc. Canada*, 11:195–208 (1908).

[16] F. Omori, "Horizontal Pendulum Diagram Obtained During a Storm," *Publications of the Earthquake Investigation Committee in Foreign Languages*, no. 21 (1905), pp. 5–8.

effect was noted, but this time a mareogram was obtained. It was found that the effect of the low near the coast was to raise the water 2.5 feet higher than the normal increase of level brought about by the tide. The weight of water following the low tilted the earth at that point to a degree which completely masked the effect of the low on the upper layers of the ground.

In an unpublished preliminary study of the relationship of gradients to microseisms recorded at Seattle, the writer found no good evidence that a connection existed.

In the study of the same problem at Sitka, the writer found a correlation coefficient between microseisms and heavy gradients of only 0.27.

From *a priori* reasoning, and from the facts presented above, we will discard the idea that a heavy gradient may produce oscillatory motion of the earth's surface.

Nonperiodic Pressure Oscillations

This section is primarily a study of the effect of cyclonic depressions on the ground surface. The existence of marked depressions in the region of a heavy microseismic storm has often excited the suspicions of seismologists, but it has always been difficult to understand just how a mere depression could cause oscillatory motion of the ground. As far as is known to the writer, no comprehensive study has been made of this phase of the problem.

It is very difficult to separate the nonperiodic variations in pressure from a discussion of the movements of cyclones. Because the phenomena accompanying intense cyclones will be discussed in a later section of this paper, the writer will confine his remarks here to results of the study of the Sitka data. This study showed that there often are increases of microseismic motion simultaneously with, or immediately following, a wave of low pressure. It is also interesting to note that the relative value of the low-pressure wave must be taken into consideration. If a pressure wave of reduction equal to 0.5 inches occurs, it makes considerable difference whether the original pressure was high, say 30.5 in., or was lower, say 29.8 in. Another qualification is the rate of reduction. If the same pressure reduction takes place in two successive occurrences, the first in 24 hours, and the second in 48 hours, the former most often accompanies the most marked ground motion. In other words, the result would seem to be governed by three factors, namely, (1) the total change of the pressure, (2) the rate of change of the pressure, and (3) the initial pressure of the area.

As has been said before, it is difficult to differentiate between simple local pressure reductions and the approach of a cyclone. When the relationship of the local atmospheric lows at Sitka to simultaneous microseismic motion was studied, a correlation coefficient of 0.51 was found. Though this factor is not great, it is a definite improvement on the surf relationship.

Periodic Pressure Oscillations

In this section it is proposed to study oscillations of air bodies independent of the lateral movement of the low- and high-pressure areas; in other words, vertical oscillations and movements of air bodies.

We may divide the periodic variations of pressure in the atmosphere into two groups: (1) regular, and (2) accidental variations.

A. REGULAR OSCILLATIONS

Type 1. Tidal Effects in the Atmosphere

This type of variation has been most ably discussed by Bartels[17] in one of a series of lectures given before the Carnegie Institution of Washington, in March, 1932.

We find outlined in Bartels' lecture several daily tides or periodic pressure changes at a given point in a given latitude. The chief among these changes are: the 24 hourly wave, the 12 hourly wave, the 8 hourly wave, and the 6 hourly wave.

Because the periods of these waves are long, the effects of the waves are not noticed as ground motion. They may have some tilting effect, but this would be so slight as to be absorbed in the daily tilt brought about by temperature changes at the earthquake observatories. These long-period waves are mentioned here simply to emphasize the fact that there are numerous atmospheric pressure variations of all frequencies. When we consider the whole number of types of microseisms, we must realize that there must be a corresponding number of causal oscillations, the frequencies of which must be comparable to those of the resulting microseisms.

Type 2. Adiabatic Changes

It has been found by meteorologists that there is a whole range of frequencies of pressure oscillations brought about by adiabatic changes in the atmosphere. Brunt[18] has given an equation for the period of such oscillations, as follows:

$$T' = \frac{2\pi}{(T/g)(B + dT/dh)} \tag{4}$$

where T' is the period of oscillation, g the acceleration of gravity, B the adiabatic lapse rate, dT/dh the temperature gradient, and T the temperature of the air at the height h.

[17] J. Bartels, *op. cit.*

[18] D. Brunt, "The Period of Simple Vertical Oscillations in the Atmosphere," *Quart. Jour. Roy. Meteorolog. Soc.*, 53:30 (1927).

In an isothermal atmosphere where $dT/dh=0$, Brunt says the period of oscillation will be given by

$$T''=\frac{2\pi}{(gB/T)^{1/2}} \tag{5}$$

In this equation, if we take T equal to 300° A., we find a period of somewhat less than six minutes.

Johnson[19] (*op. cit.*, p. 24) has discussed the paper by Brunt, and exhibits a table of periods that are to be expected from certain variations of the temperature gradient as compared with the adiabatic rate. The table is given below (and is here entitled table 2):

TABLE 2

COMPUTED BAROMETRIC OSCILLATION PERIODS AS A FUNCTION OF TEMPERATURE GRADIENT

Period (min.)	Temp. grad. (dT/dh)		Period (min.)	Temp. grad. (dT/dh)
1	3.3 B	inversion	7	−0.33 B
2	7.4 B		10	−0.66 B
3	2.7 B		15	−0.85 B
4	1.1 B		20	−0.92 B
5	0.34 B		30	−0.96 B
5.8	0.0 B	isothermal	40	−0.98 B
			50	−1.00 B

With reference to the period of 50 minutes, shown in his table, it must be said that Brunt is of the opinion that there is no oscillation, and that any displaced particle will stay where put. Of course, with a period of 50 minutes, oscillation would be difficult to detect.

Gherzi[20] has noted the effect of barometric oscillations on the ground in producing wave motion. In table 3 will be found the occurrences which he has noted. Several of these occurrences were simultaneous with either the passage of a continental depression over the Yangtse Valley or the existence of a thunderstorm.

[19] N. K. Johnson, "Atmospheric Oscillations shown by the Microbarograph," *Quart. Jour. Roy. Meteorolog. Soc.*, 55:19 (1929).

[20] E. Gherzi, "On Some Long Waves Registered on Galitzine Vertical Component at the Zi-ka-wei Observatory," *Proc., 4th Pacific Sci. Congr.*, Java, 2A:357-362 (1930).

TABLE 3

MICROSEISMS CORRELATED WITH BAROMETRIC OSCILLATIONS AT ZI-KA-WEI

Date	Duration (minutes)	Number of waves	Period (minutes)
1921—Aug. 26	146	40	1–3
1924—Jan. 14	100	....	......
1924—May 26	52	5	8
1926—Apr. 2	9	5	8
1927—Jan. 14	57	10	4–6
1927—May 5	22	3	5–6
1928—Jan. 26	18	5	4
1928—Feb. 25	16	1	10
1928—Mar. 1	24	11	3
1928—Mar. 20	55	2	7
1928—Mar. 29	17	6	5
1928—May 13	43	6	6–8
1928—July 26	....	6	18
?	180	....	1

B. ACCIDENTAL OSCILLATIONS

Type 1. The Tropical Cyclone

Gherzi[21] has suggested several times that "pumping" in the center and near-center of a cyclonic depression is the cause of the ordinary type of microseism. It is fortunate that we have for study the results of a preliminary investigation, by the writer, of the microseisms recorded at Saint Louis University Seismological Observatory during the hurricane of August 21-24, 1933, which occurred on the Atlantic Coast, especially in Virginia and Maryland. There are two factors which make this study a convenient one, namely: (1) the storm occurred in the season in which microseismic motion is ordinarily at its lowest ebb, so that there was no confusion of measurements of the records; and (2) the storm center passed directly over Washington, D. C., where there was a compensated syphon type of microbarograph.

On the evening of August 19 this storm center formed some 1700 kilometers off the Carolina coast and advanced northwestward with an average velocity of 22.8 km/hr. The initial form was that of the ordinary temperate-zone cyclone. However, as it approached the coast, it grew more intense and gathered speed. When it reached Cape Hatteras, on the night of August 22-23, it had assumed the proportions and form of a tropical hurricane. As it crossed the coast, the barometric pressure in the storm center was approximately 28.9

[21] E. Gherzi, "Le Problème des microseismes à groupes," *Zeitschr. f. Geophysik*, 4:147 (1928); "Etudes sur les microseismes," Observatoire de Zi-ka-wei, *Notes de Sismologie*, N° 5 (1924); "Microseisms Associated with Storms," *Beitr. z. Geophysik*, 25:145 (1930).

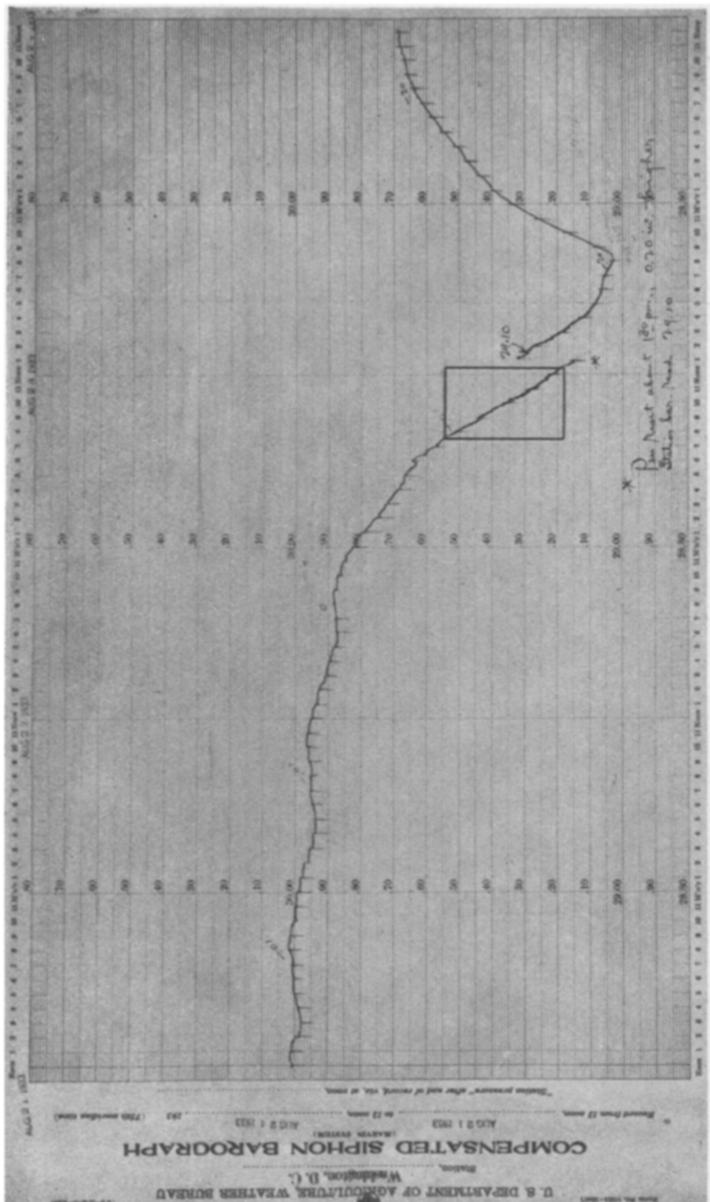

Fig. 1*a*. Barogram taken during the passage over Washington, D. C., of the hurricane of August 22–23, 1933.

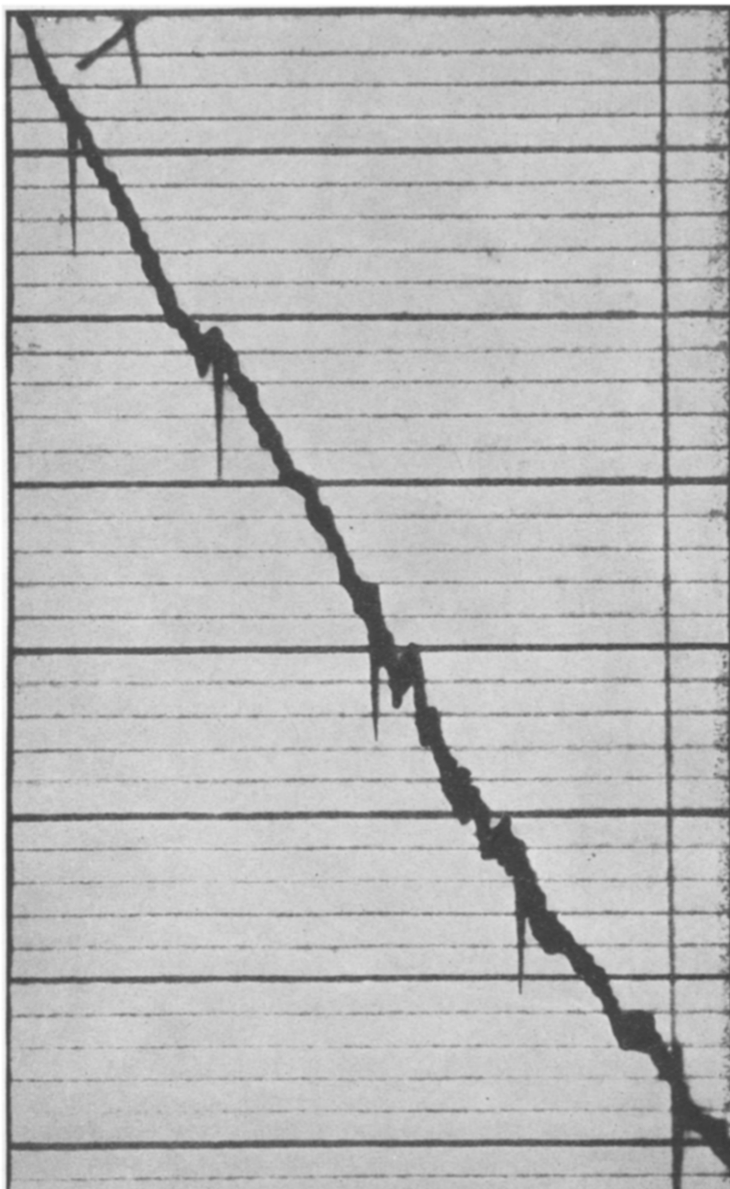

Fig. 1*b*. Enlargement of the "ragged" part of the barogram, which represents the "pumping" effect which has been postulated by Gherzi as causing the presence of microseisms.

inches of mercury. From a point about 100 kilometers west of Norfolk, Virginia, the storm turned northward, advanced up Chesapeake Bay, and then swerved somewhat northeastward. From this point on, the storm center began to fill up, and by the time it reached Montreal on the morning of August 25, it had partly dissolved and divided into two parts, and became stationary.

TABLE 4

PERIODS AND AMPLITUDES OF MICROSEISMS AT ST. LOUIS COMPARED WITH AMPLITUDES OF BAROMETRIC OSCILLATIONS AT WASHINGTON

Date (1933)	Hour (GMT)	Period (sec.)	Ground displacement (mm.)	Barometric oscillations (mm.)
Aug. 21	18	5	0.00021	0.0069
22	0	5	0.00028	0.0069
22	6	5	0.00024	0.0103
22	12	5	0.00028	0.0138
22	18	4	0.00028	0.0207
23	0	4	0.00035	0.0207
23	6	4	0.00056	0.0414
23	12	4	0.00063	0.0551
23	17	4	0.00127	0.1975
23	18	4	0.00063	0.1102
24	0	4	0.00049	0.0414
24	6	4	0.00031	0.0069

It is the part of the path taken between the hours of 8 P.M., August 22, and 8 P.M.., August 23, which the writer proposes to study.

At the second hour, G.M.T., of August 23, the cyclone was some 200 kilometers off the Carolina coast. At the tenth hour it crossed the coast. It was at this time that a marked increase in microseismic motion was observed at Saint Louis. However, it was not until the seventeenth hour that the maximum amplitudes were recorded by the Saint Louis seismographs. It is seen on the Daily Weather Map that at the fourteenth hour the center of the cyclone was approximately 100 kilometers west of Norfolk. Three hours later the maximum microseismic displacements were measured at Saint Louis. Now it so happens that the approximate diameter of the center of the cyclone was 170 kilometers. It is noticeable that the maximum microseismic motion did not occur until just the time at which the entire area of the center of the cyclone was over land. It was also at this hour that the maximum pumping effect was registered on the barograph at Washington.* Most remarkable is the fact that the time variation

* Loaned through the kindness of the Director of the United States Weather Bureau, Washington, D. C.

of pumping amplitudes at Washington corresponds exactly with the time variation of microseismic displacements recorded at Saint Louis. This relationship is shown in table 4. The pumping action may be seen in figure 1*b* (p. 337).

The objection that the microseisms must "surely" have arisen from surf may legitimately be made. The writer has also taken this into consideration, and was informed by the United States Coast and Geodetic Survey[22] that the most noticeable effect was the coastal loading by the tremendous amount of water pushed toward the shore by the rapidly moving storm center, with its accompanying high winds. It is quite possible that the tidal loading did produce tilting of the earth in that region, but it is questionable whether the microseismic motion may be attributed to that source. The sharpness of the increase both of the amplitude of the microseisms and of the pumping is remarkable, and their simultaneity should preclude any other cause.

Type 2. "Extratropical" and Temperate Lows

It has often been noticed that there are intense cyclones far from the sea which do not appear to produce microseisms of great amplitude. It is believed that this may be accounted for by the structure of the low, which might be influenced by its distance from the nearest body of water of oceanic size. This is substantiated by the often repeated statement that microseisms are seen to increase with the strength of a storm as that storm approaches the coast, and then to weaken as the storm passes over the coastline and becomes less severe.

There now arises the question, whether or not the storms of the Bering Sea have the same essential structure and exhibit the same pumping effect as do the tropical cyclones. We must first consider the types of cyclones which appear to generate the largest microseismic displacement.

Most of the more intense lows of the Bering Sea are of the *round* type, which is also characteristic of the centers of the tropical lows. The *trough* appears frequently, and the *elliptic* type is often seen also. Many occurrences are difficult to classify, since the configuration of the isobars changes rapidly.

The intensity of many of the lows of the Bering Sea in the storm season is remarkable, often reaching the minimum value of from 28.4 inches to 28.2 inches of mercury. If the storm centers of the Bering Sea suffer the same degree of pumping as do the typhoons described by Gherzi,[23] in which the pressure oscillations amount to 5 millimeters or more, the propagation of the disturbance to the ocean floor through the medium of longitudinal waves, and from there to the recording station in the form of microseisms, would not be hard to visualize.

[22] Personal communication from J. H. Hawley, Acting Director, dated September 11, 1933.

[23] E. Gherzi, "Etudes sur les Microseismes," Observatoire de Zi-ka-wei, *Notes de Sismologie*, N° 5 (1924).

In order to test this theory, the writer examined the Sitka data with regard to the relationship between microseismic activity and the existence of low-pressure areas in the Bering Sea, and found a correlation coefficient of 0.80. A weakness is here admitted in the fact that there is no microbarograph in operation at Sitka. However, the work of Shida[24] may be cited. This Japanese

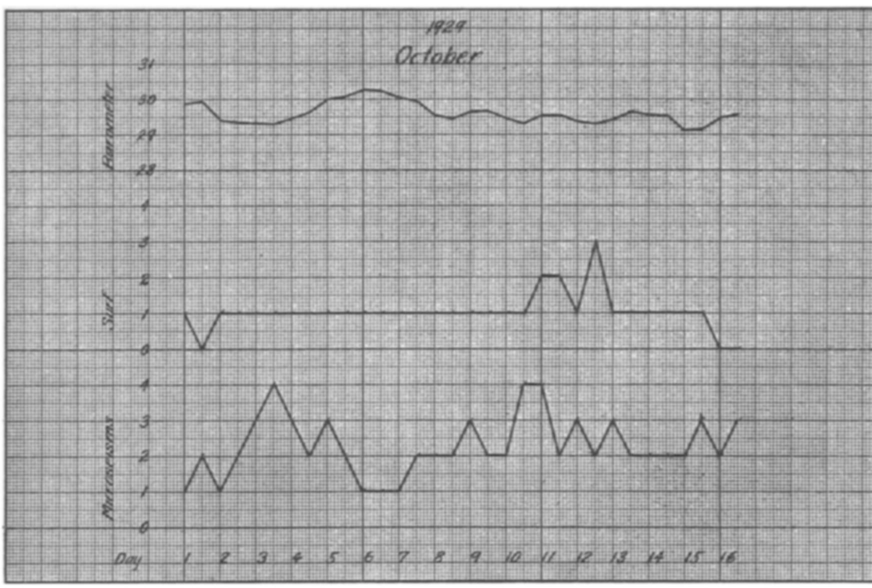

Fig. 2. One of 72 graphs of the Sitka data, from which the various correlation coefficients were drawn. Note the correspondence of microseisms with low-pressure waves; also the lack of correlation with surf.

scientist, while operating a microbarograph of his own design, found that there were atmospheric oscillations at Tokyo with periods averaging about six seconds. Periods of twelve seconds were also conspicuous. It is fortunate that this work was done in the same range of latitude, and near the same body of water, as Sitka. It is entirely possible that these oscillations are present almost continuously and are greater in winter than in summer. An investigation of this effect is being carried on at Saint Louis University by the writer and Dr. J. B. Macelwane, S. J. So far, though preliminary records have been made, it is impossible to give any definite conclusion.

Motion of Period Greater than Seven Seconds

Aside from the several types and classes of microseisms of period less than seven seconds, there are also recorded microseisms of period greater than seven

[24] T. Shida, *Nature* (Review), 82:45 (1909).

seconds. These oscillations have periods ranging from seven seconds to well over one minute. Various causes have been suggested for these motions, but, as far as is known to the writer, no conclusive proof pro or con has ever been found. As the study of the data from Sitka offers nothing which might bear on this problem, the writer will limit his remarks in this section to a very few words.

Motion from the Effect of Freezing in the Upper Layers

The reader is referred to Klotz[25] and to Gutenberg[26] for more complete data on the subject. Gutenberg found something of a correlation between the temperature of the upper ten centimeters of the ground and microseismic motion, provided that the temperature was at freezing temperature or lower.

J. S. O'Connor, S. J.,[27] informed the writer: "Without making any close comparative study, I have noticed that the amplitude of the microseisms increases considerably during a sudden drop in temperature, especially when accompanied by frost."

A study conducted at Florissant of the correlation between temperature and microseisms yielded no practical results.

Motion from the Effect of Turbulence and Wind Friction on the Ground Surface

Much has been said of the power of wind to disturb the surface of the ground so as to produce microseisms of period between thirty and ninety seconds. It is believed that there is a vertical component of wind motion which may assist in this effect. Taylor[28] has given an expression for the pressure variation from turbulence in an air movement which is gusty. He found the relationship

$$\Delta P = \tfrac{1}{2} d u'^2 \tag{6}$$

where ΔP is the average variation in pressure, d is the density, and u' is the variation in wind velocity from the mean. Statistically, the variations in velocity correspond exactly with a pressure distribution which travels along with the mean wind. It will be observed in the illustrations given by Taylor that there are at least ninety gusts per hour. If there were a traveling pressure difference with each gust, a frequency of 90 gusts/hour would produce periods of approximately forty seconds, which is certainly within the range of period of the so-called "wind" microseisms.

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[25] O. Klotz, "Microseisms," *Jour. Roy. Astron. Soc. Canada,* 11:195–208 (1908).

[26] B. Gutenberg, "Bodenunruhe durch Brandung und durch Frost," *Zeitschr. f. Geophysik,* Jahrgang 4, pp. 246-250.

[27] Personal communication to the author, dated December 17, 1931.

[28] G. I. Taylor, "Turbulence," *Quart. Jour. Roy. Meteorolog. Soc.,* 53:209 (1927).

CONCLUSIONS

The following points sum up the writer's reasons for a conclusion in favor of the atmospheric pumping hypothesis of the cause of microseisms.

(1) Low correlation coefficient between surf and microseisms at Sitka (0.27).

(2) High correlation coefficient between microseisms and the existence and movements of cyclones at Sitka (0.80).

(3) The correlation of atmospheric pumping in the storm of August 23, 1933, with microseisms recorded at Saint Louis.

(4) The results of the investigation by Shida of the periods of oscillation of the atmosphere at Tokyo.

(5) Various other minor points outlined in the foregoing pages.

It seems possible to merge the Banerji theory with the atmospheric pumping hypothesis, in that atmospheric pressure oscillations over deep water may be propagated to the sea bottom, there to be transformed into microseismic motion.

It is possible that, if the microbarographs in use at present possessed greater magnification and trace speed, we should be able to see and study atmospheric oscillations with periods ranging from a fraction of a second to as much as six or seven seconds. Much further study is required if this problem is to be solved conclusively.

ACKNOWLEDGMENTS

The writer wishes to express his appreciation to Mr. Franklin P. Ulrich, of the United States Coast and Geodetic Survey, for the loan of the data from which these conclusions were drawn; to the Washington Office of the United States Weather Bureau, for the loan of the microbarogram of the hurricane of August 23, 1933; to the United States Coast and Geodetic Survey, for the loan of data pertaining to the problem; to the Seattle office of the United States Weather Bureau, for the loan of weather maps for the period studied, 1929-1931, inclusive; to Dr. James B. Macelwane, S. J., Director of the Department of Geophysics of Saint Louis University, for many helpful criticisms and remarks; to Dr. Perry Byerly, Professor of Seismology in the University of California, for thorough criticism and helpful suggestions; and to his wife, Doris, for many months of untiring assistance in the preparation of data.

SAINT LOUIS UNIVERSITY,
June, 1934.