AN EXPERIMENTAL INVESTIGATION OF THE NATURE AND ORIGIN OF MICROSEISMS AT ST. LOUIS, MISSOURI*

PART ONE

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INTRODUCTION

MICROSEISMS are natural, regular ground oscillations that are not produced by earthquakes, nor by artificial means such as dynamite explosions or traffic. They have always been a nuisance to astronomers in their observations, and a puzzle to seismologists ever since the early days of instrumental seismology. This puzzling character is perhaps the reason for the many names given them in the different countries where they have been studied.

The Germans have variously designated them as "Pendelunruhe" (Laska),[1] "mikroseismische Unruhe" (Hecker 1915, Remp), "seismische Bodenunruhe" (Gutenberg 1911, Tams, Schunemann, Schneider, Mendell, Mühlen), "Bodenunruhe" (Gutenberg 1911, Laska), "mikroseismische Bewegungen" (Hecker 1913, Meisner), "mikroseismische Bodenunruhe" (Jung, Mainka), "mikroseismische Pulsationen" (Wiechert 1907), "mikroseismische Flächenbewegungen" (Mazelle). Furthermore, in accordance with the German theory of origin they are also "Brandungsbewegungen" (Linke). More recently they have been called "natürliche Bodenunruhe" (Krug).

The English-speaking investigators have preferred such names as "microseisms" (Archer, Banerji 1930, Klotz 1908, Lee 1932, Repetti, Macelwane and Sprengnether), "microseismic tremors" (Burbank), "microseismic disturbances" (Lee 1932, Whipple), "microseismic waves" (Leet 1934, Lee 1935), "tremors" and "micro-tremors" (Milne).

In the French language the word "microséismes" or "microsismes" has been used almost exclusively, either as a noun or in its adjective form "microséismique." Thus "microséismes" (Somville 1915, Gherzi 1924*a*), "oscillations microséismiques" (Galitzin 1911), "mouvement microséismique" (Lacoste 1926), "mouvement microséismique de surface" (other authors).

The Japanese seismologists have always preferred in their translations the original terms "micro-tremors" (Omori 1908), "pulsatory oscillations" (Omori 1913, Wadati), "surface tremors" (Nagaoka), "seismic pulsations" (other authors).

In the Italian language, microseisms are known almost exclusively by the

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[1] For this and other references to authors and their works, see the List of References on pp. 80–84.

original name given to them by Bertelli, "microseismi" (Bertelli, Zanon 1936); in Spanish, "microseismos" (Navarro-Neumann 1931).

Nineteenth-century investigations.—It seems quite certain that microseisms, as such, were first studied at Florence, Italy, by the Barnabite monk, Timoteo Bertelli (1826–1905), whom Milne called the "father of systematic microseismical research" (p. 321). Bertelli spent three years, from 1869 to 1872, making a series of simple experiments and studying the small spontaneous movements of a pendulum suspended in his cellar. Such movements had been observed some centuries before, but full credit should be given to Bertelli for having made thousands of observations during this three-year period, for suggesting the causes of the tremors, and for introducing two names for them, "microseismi" and "moti tromometrici," the latter from tromometer or pendulum. At the end of November, 1872, he arrived at the three conclusions: "(i) The microseismic movements of an isolated pendulum often occur contemporaneously with distant earthquakes; (ii) others occur during continued barometric depressions; and (iii) the movements have a maximum in winter and a minimum in summer" (p. 92). Bertelli influenced a wide circle. In 1874, daily tromometric observations were made at five stations in Italy; ten years later, at thirty.

In Japan, microseisms have been studied chiefly by two seismologists, J. Milne and F. Omori. Following their investigations, pulsatory oscillations are frequently referred to and are attributed to volcanic activity, the passage of deep barometric lows, or the existence of heavy ocean swells.

Immediately after the registration of the first distant Japanese earthquake of April 17, 1889, at Potsdam and Wilhelmshaven, by instruments erected by von Rebeur-Paschwitz and Zöllner, the study of earthquakes and microseisms was begun in Germany. The term "mikroseismische Bewegungen" was then introduced from the Italian language, although unwillingly, because "diese hat mit wirklichen seismischen Erscheinungen nichts zu tun" (Rebeur-Paschwitz, p. 355).

Early twentieth century.—Since the beginning of the twentieth century, with new instrumental improvements, and the establishment of an International Seismological Association, the problem of the study and cause of microseisms has received increased attention. At almost every international seismological meeting a special committee has reported upon new findings on the cause of microseisms (Schünemann, Somville 1915). It was at the Second International Conference, which was held at Strasbourg in July, 1903, that Wiechert proposed publicly his ideas on the origin of microseisms, saying "dass die Störungen [microseisms] von der Meeresbrandung herrühren" (p. 41).

Most of the Japanese seismologists consider microseismic waves as stationary waves. This is the belief of Kishinouye (p. 610), of Nagaoka (p. 17), of Honda (p. 178), and of Matuzawa according to Iida (p. 505). Probably it is thus generally held because Omori compared the records of the pulsations taken at Tokyo and Hitotsubashi, both stations being in Tokyo and about 2 km. apart, and reported that "it was found impossible to identify the individual vibrations at the two places" (1913, p. 16).

Later investigations.—It is commonly assumed today by European and American seismologists that microseismic waves are of the progressive type and not simply stationary. Some authors (e.g., Gutenberg 1931, Lee 1935) have considered them to be true Rayleigh waves; others (e.g., Leet 1934) have found no Rayleigh waves in their study of microseisms.

Iida (p. 504), Lee (1934, p. 245), and others are convinced that microseisms are greatly influenced by the geologic and topographic conditions of the region in which they occur. These views are strongly criticized by Banerji (1935) and Zanon (1938).

At different times, attempts have been made to determine the velocity and the wave length of microseisms. Omori, in Japan, in February, 1908, obtained only negative results. Hecker made a trial at Strasbourg in 1915, but his results were not very satisfactory because of his rather inaccurate and primitive methods: "Only the observations of one day could be used and even on this particular day microseisms were not strong" (1915, p. 32).

Mr. J. J. Shaw in the years 1918 to 1922 was able to identify individual microseismic waves at stations 3, 4, and even 16 km. apart. "The method gave some evidence that microseisms came from a northwesterly direction to West Bromwich" (p. 52.)

From January to March, 1927, Nasu and Kishinouye set temporarily three horizontal seismographs near the Seismological Institute of the University of Tokyo to assist their study of the phase relation of microseisms at different places. The observations, however, were "not sufficient to yield definite results" (p. 153).

Krug undertook during March, May, September, and October, 1936, and in January, 1937, the determination of the velocity of propagation and the direction of microseisms at Göttingen. The stations he used were at the corners of an isosceles triangle, the two equal sides measuring about 1400 m. each. For waves of 4 to 8 sec. he found a velocity of 1100 ± 200 m/sec., which seems much too low. "Ob dieser unerwartet niedrige Wert zur Ausbreitung der Energie oder zur Ausbreitung einer bestimmten Phase einer kombinierten Welle gehört, konnte nicht entschieden werden" (p. 346). An average of 80 per cent of all the readings gave a direction N 63° E$\pm$20°. He also found some correlation between the barometric depressions on the Norwegian coast and the intensity of microseisms at Göttingen.

For the purpose of studying short air-pressure oscillations and their possible relationship to microseisms, several microbarographs have been designed and constructed.

The first microbarograph known, according to Johnson (p. 19), is one described in the *Quarterly Journal of the Meteorological Society* (31:19, 1905).

Klotz, of Ottawa, mentions (1911, pp. 205–206) a Shaw-Dines microbarograph for rapid differential pressure, not absolute pressure, with a magnification of 20, used as an auxiliary instrument in the "interpretation of seismograms."

The Japanese, Shida (Somville 1915, p. 45), constructed a microbarograph which was simply an aneroid barometer designed to record photographically.

Recently, Suzuki and Omori made a study of the records of three "leaking microbarographs" installed at three stations in Japan four miles apart. They found for the air oscillations wave lengths of 13 to 25 km., a velocity of propagation of 20 to 50 m/sec., and periods of 6 to 11 min. at levels of 3 to 8 km.

Finally, Dr. Hamilton Z. Baird, of the Christ Church Observatory in Australia, in a personal communication to the Rev. James B. Macelwane, S.J., writes of a new microphone barograph. Details of its construction are not given, but preliminary estimates lead the inventor to think that "the pressure oscillations cannot directly cause microseisms."

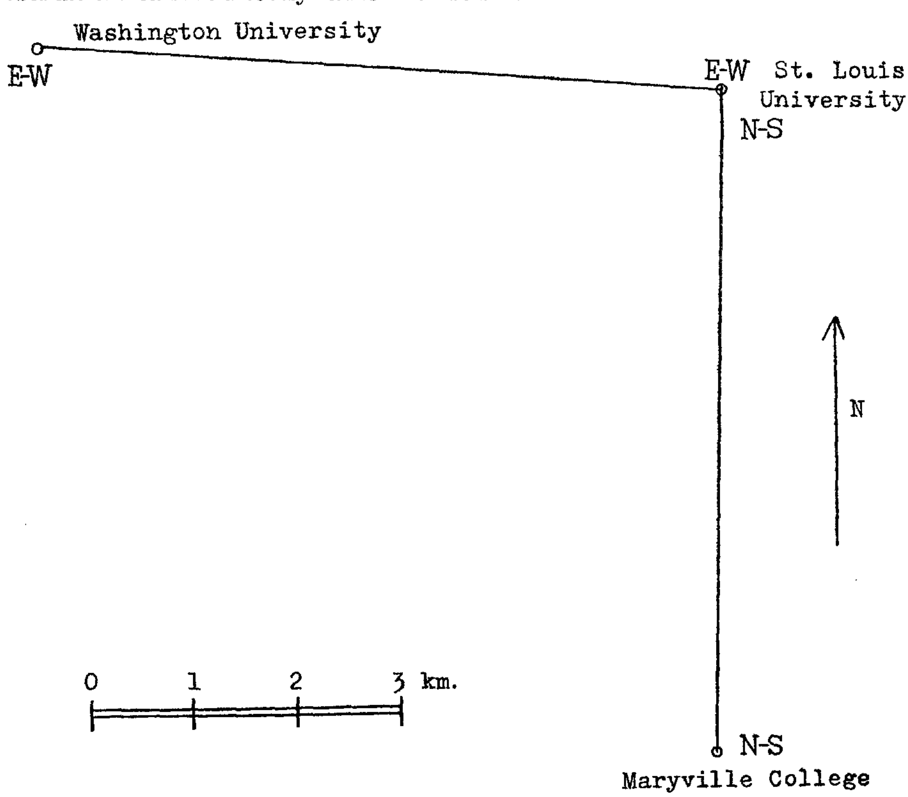


Fig. 1. Relative positions of experimental stations.

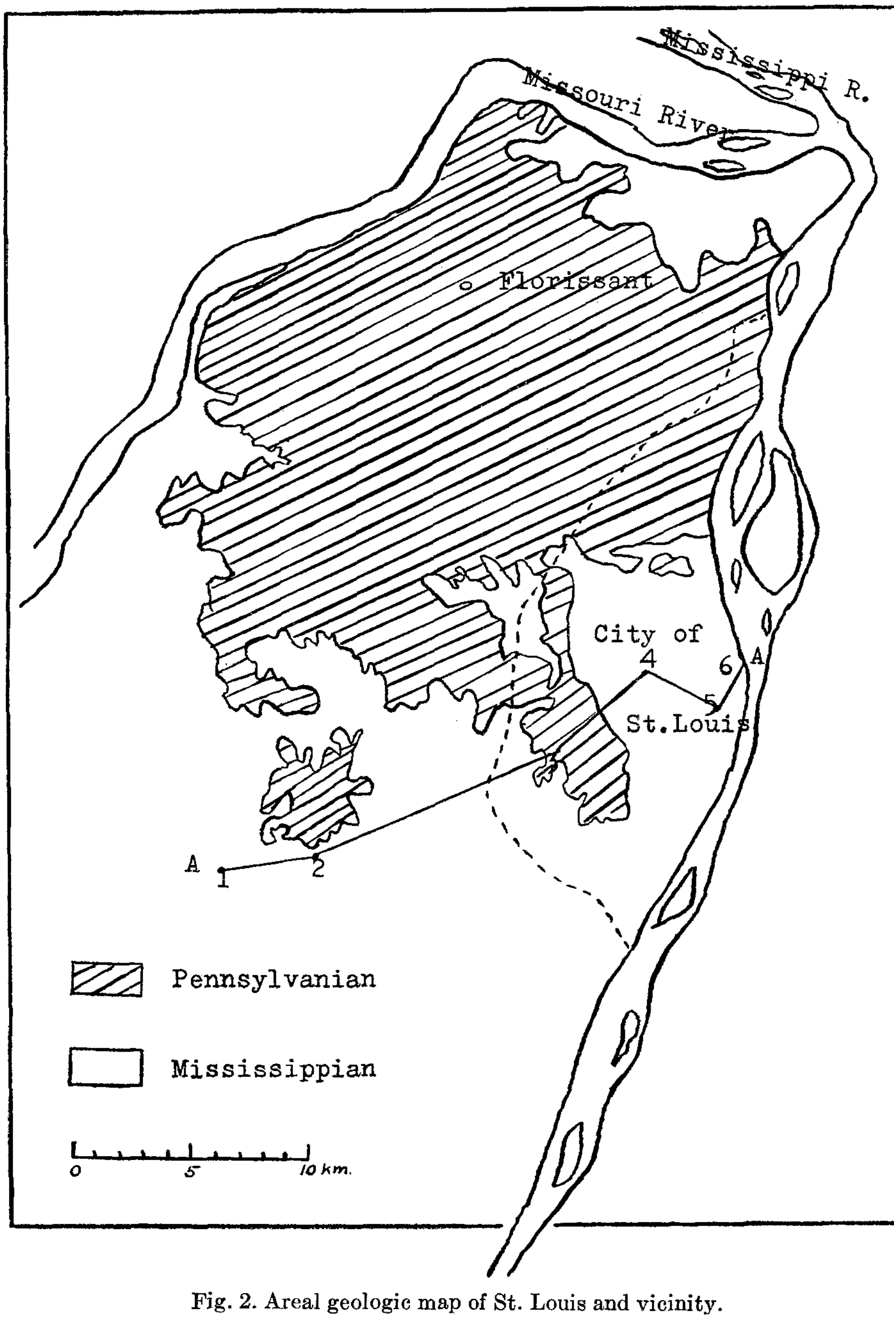


Fig. 2. Areal geologic map of St. Louis and vicinity.

Regarding the different types of microseisms, a rather complete classification of the oscillations recorded by seismographs in terms of probable causes is found in Bradford's work (1934, p. 3).

The Problem: How Approached

The present investigation has been restricted to microseisms of the most common type, namely, those varying in period from 3 to 9 sec. Attention has been focused on the traveling nature of these waves, and consequently on such problems as their direction of propagation, their speed, their amplitude and period variations, their wave length, the motion of a ground particle, and their origin.

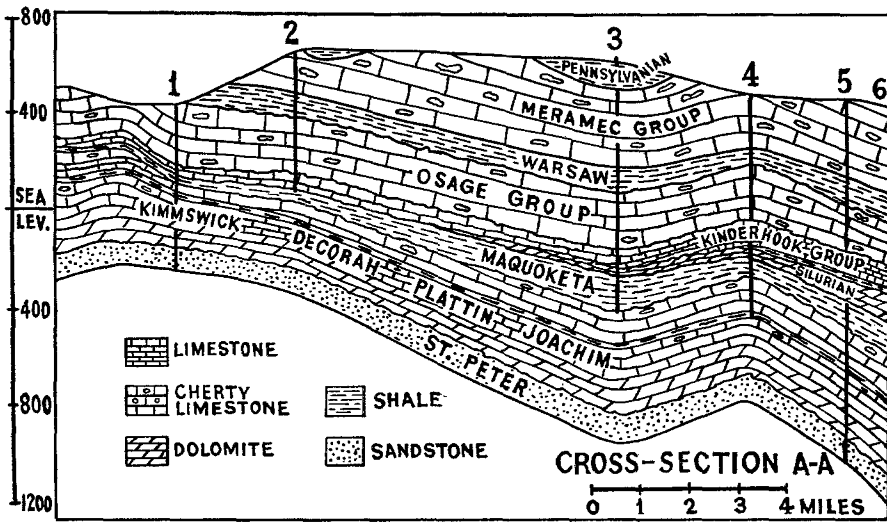


Fig. 3. Regional structure of the rocks in the city of St. Louis. (By courtesy of the Missouri Geological Survey.)

The following instruments have been used: four horizontal electromagnetic seismographs specially designed for recording microseisms, two microbarographs constructed with the purpose of studying the short air-pressure oscillations, and a special pendulum and "tickler" combination for marking signals on the records every six seconds. The four seismographs were arranged in the form of a network: two E–W components, one at the St. Louis University Gymnasium and one 6.4 km. almost due west, at Washington University; and two N–S components, one at the St. Louis University Gymnasium and one 6.3 km. almost due south, at Maryville College. These distances were chosen because they are presumably about one-quarter of a microseismic wave length.

Figure 1 shows the location of the seismographs in the city of St. Louis and their relative position. Maryville College lies S 1° W from St. Louis University, and Washington University (Wilson Hall) lies approximately S 94° W from St. Louis University.

The geologic foundations of the St. Louis University and Maryville College stations consisted of hard Mississippian limestone. The pier at Washington University rested on Pennsylvanian shale. (See figs. 2 and 3.)

A perfect synchronization of time marks was effected from a single clock by means of leased telephone wires. The pendulum and "tickler" combination was used to send signals at shorter intervals than the regular one-minute clock marks and thus to increase the number of simultaneous observations. Thus the almost perfect right-angled triangle formed by the three stations in St. Louis, the accurate timing system, and the instrumental homogeneity were to give rather precise information concerning the phase differences and the direction and speed of microseismic waves.

Instruments Used

Seismographs.—The design chosen required a small horizontal pendulum, with tension-hinge supports, induction transducer, and electromagnetic damp-

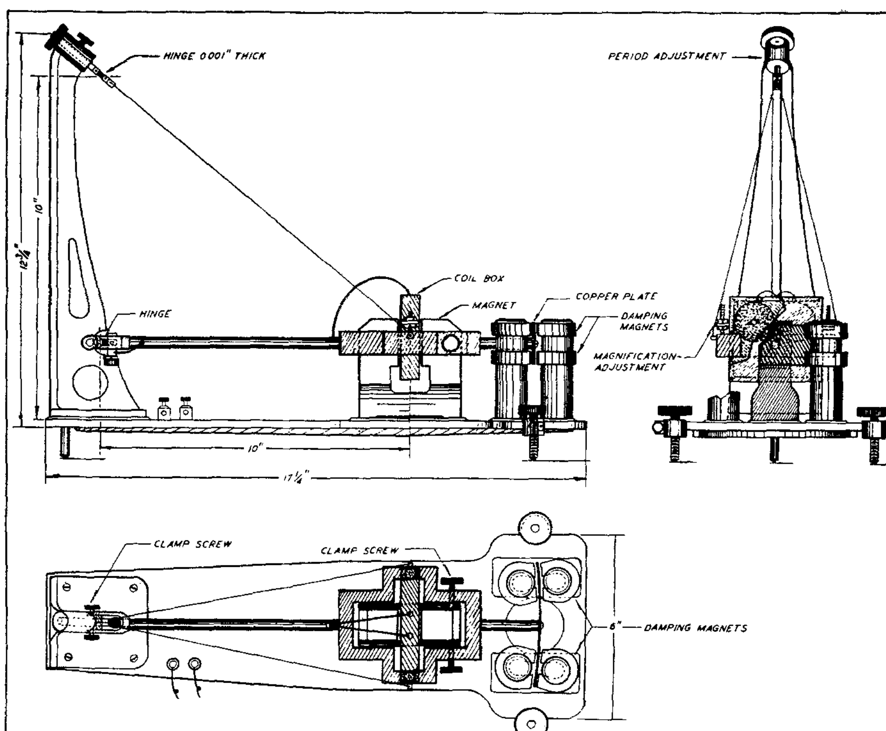


Fig. 4. Type of seismograph used, as seen from one side, one end, and from above.

ing. The instruments, equal in size, and closely similar in every respect, were constructed by the W. F. Sprengnether Instrument Company of St. Louis. (See fig. 4.) The current from the coils of the transducer was led to a Leeds and Northrup type-R galvanometer of six seconds period, with critical resistance of about 10,000 ohms. The period of the pendulum was adjusted to synchro-

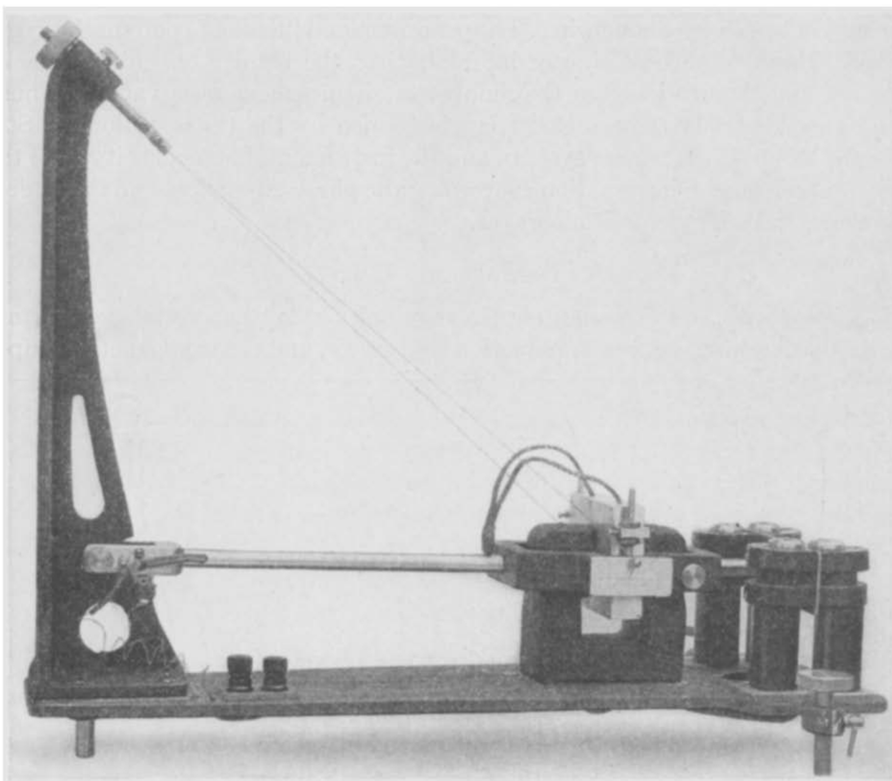


Fig. 5. Type of seismograph used: photographic side view.

nism with that of the galvanometer, so that the whole system was in resonance with the microseisms that were being studied. The dynamic magnification of the seismographs was about 1340.

Figure 5 gives a side view of one of the seismographs. The coil box is supported in the field of a strong horseshoe magnet of "Alnico" alloy, and the wires are lead back through the hollow boom to binding posts on the frame. A detailed description of the seismographs is given by Macelwane (Macelwane and Sprengnether).

Electromagnetic microbarographs.—These instruments were designed by J. B. Macelwane, S.J., for the purpose of recording air oscillations of the same order of frequency as the microseisms, and were built in St. Louis by the W. F. Sprengnether Instrument Company, with the collaboration of D. C. Bradford and V. M. O'Flaherty, S.J. They consist essentially of a large brass air chamber over the open end of which is tightly stretched and clamped a rubber diaphragm. (See fig. 6.)

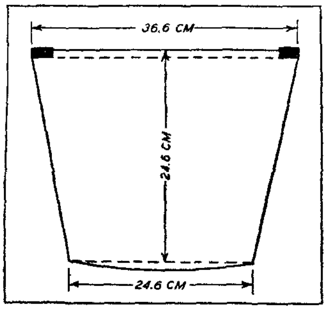


Fig. 6. Shape and dimensions of brass kettle.

A short solenoid was attached to the diaphragm at the center with its axis normal to the rubber surface and its weight supported from the frame by two vertical wires balanced by pairs of rubber stays below, spaced at angles of 120° each and stretched parallel to the diaphragm. Into the air core of the solenoid was inserted without contact one pole of a cobalt-steel bar magnet rigidly supported by the frame. (For further details of construction see Macelwane and Ramirez.)

In order to determine the total magnification of the small movements of the membrane due to air oscillations, a mechanical-optical device was employed. (See fig. 7.) It consisted in attaching one end of a thread to the coil of the microbarograph, the other end being wound around a tiny cylinder which rested on agate bearings. The thread was kept taut by means of a hair spring which tended to rotate the cylinder and a plane mirror glued to it with shellac. The amplified motion of the coil was about 2200.

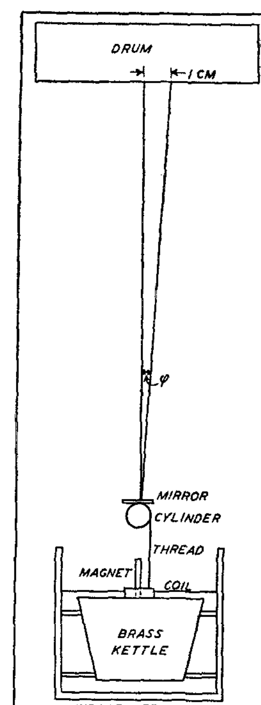


Fig. 7. Device for testing magnification.

By comparing the mechanical-optical magnification with the galvanometric magnification, the latter was found to vary with the period of the vibrations, being greatest for those vibrations of the membrane which had about the same period as the galvanometer, that is, about 6 sec. (See fig. 8.)

A special triple drum 5 feet long, driven by a General Electric synchronous motor with a paper speed of 60 mm/min. was used in the St. Louis seismic vault for the recording of the N–S and E–W components established there. (See fig. 11.) Two Henson seismograph drums were used at the other two stations, Maryville College and Washington University, with the same paper speed of 60 mm/min.

"Tickler."—A "tickler" was devised and constructed in combination with a pendulum beating seconds.

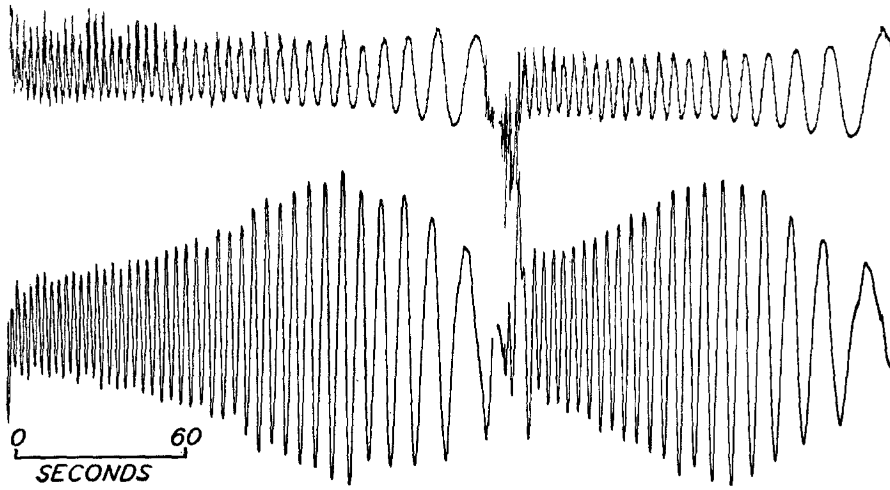


Fig. 8. Galvanometric magnification (bottom) and mechanical-optical magnification (top) when the microbarograph membrane was forced to vibrate with a slowly and evenly increasing period.

The essential part of the tickler consisted of two electromagnetic coils set side by side in a vertical position. (See fig. 12.) An iron plate was mounted on top of the iron cores of the two coils. On one of the iron cores there was a hinge around which the iron plate could move, and on the other iron core there was inserted a coil spring that pushed up the iron plate every time this plate was attracted by the electromagnet. The up-and-down motion of the mounted iron plate turned a wheel, one complete revolution every eight contacts, and kept

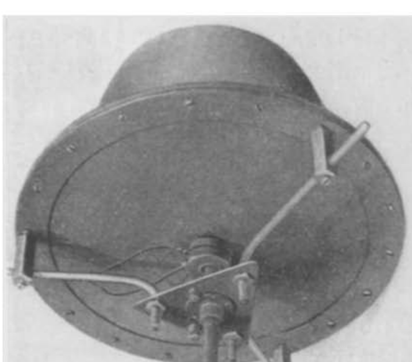


Fig. 9. A close view of the microbarograph.

Fig. 10. Temporary housing of the microbarograph at Florissant. The instrument worked, for the most part, within the seismic vault.

the pendulum in motion by means of mechanical impulses given by an attachment of the iron plate every time the pendulum itself closed the circuit. The 8-sec. signals were sent by the large wheel at every turn on a circuit different from the clock and tickler circuits.

Measurement of Amplitudes and Periods

In the measurements of the amplitudes and periods of microseisms from the seismograms, the following procedure was followed. From a period of ten

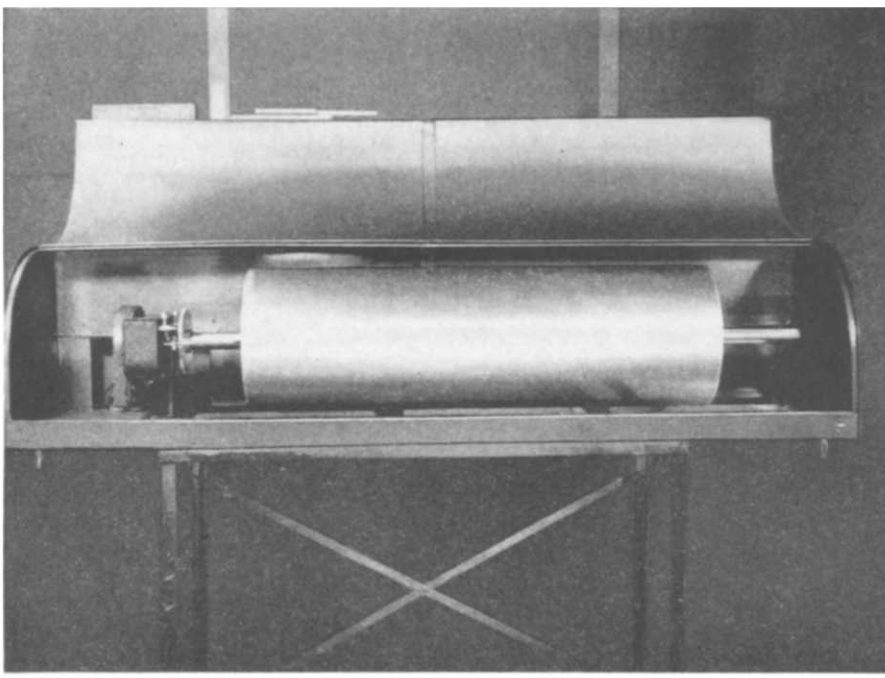


Fig. 11. The triple drum.

minutes centered at the hour the most conspicuous groups of microseisms which persisted for about thirty seconds were selected. A convenient transparent millimeter scale was used for measuring the mean period of the whole group and the mean amplitude (half the crest-to-trough distance) of the largest three consecutive oscillations. These measurements were made every hour each day through July, August, and September, 1938, and also for the important storms of October, November, and December. The smaller microseisms of these last three months were measured only about four times a day at convenient intervals. The amplitudes as scaled from the records in millimeters could usually be used directly for the determination of relative magnitudes; but sometimes it was necessary to convert the trace amplitudes to amplitudes

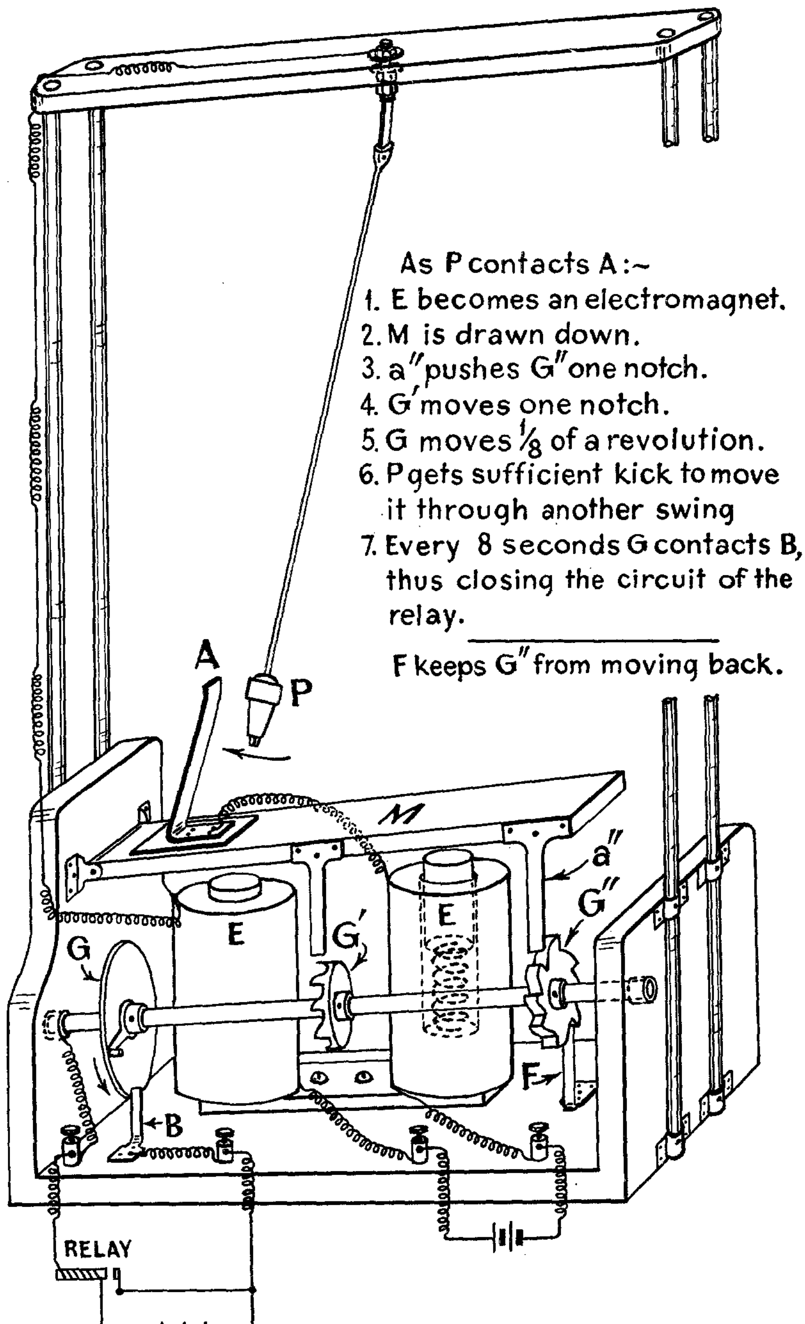


Fig. 12. The "tickler."

of ground motion in microns, using the appropriate factor. The periods are expressed in seconds.

Amplitudes.—A general idea of the amplitudes of microseisms can be gained from the curves plotted for each of the months from July to December, 1938.

July, 1938: Microseisms during July hardly reached 1 mm. in amplitude. These larger amplitudes occurred only in a short storm of the first two days of the month; the rest of the amplitudes were hardly measurable, with an average of 0.4 mm. (See fig. 13.) The frequency of occurrence of the various amplitudes

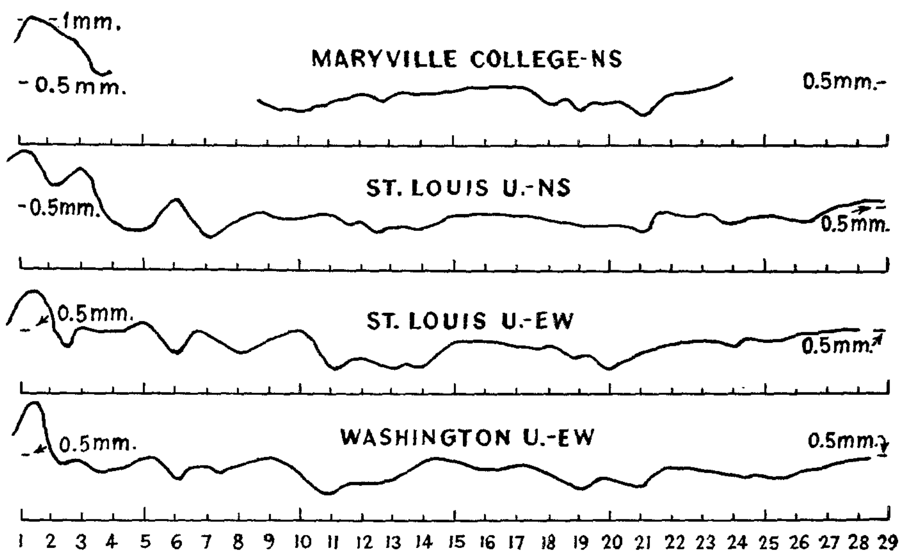


Fig. 13. Amplitude of microseisms at the three stations in St. Louis, July, 1938. Here 1 mm. has been amplified twenty times; that is, 20 mm. in the graph equals 1 mm. in the original record. In succeeding figures the amplification is only 10; that is, 10 mm. in the graph equals 1 mm. in the original record.

or the number of times that a particular amplitude occurred in July has been summarized in table 1.

August, 1938: The various microseismic storms for August (see fig. 14) are more pronounced than those of July. The scale has been reduced by half. The average amplitude is approximately 0.56 mm. The first large microseismic storm started suddenly on August 15 and there was some microseismic activity in the following intervals: 3–5, 12–13, 20–25, and 28–30. The frequency of occurrences of amplitudes for the month is shown in table 2.

September, 1938: September is characterized by the second strongest microseismic storm of the six-month period. This storm occurred simultaneously with the New England hurricane. The first part of the month was relatively quiet; in the second part, two storms occurred. The average amplitude of the readings is about 0.65 mm., which is much higher than the figure of the preced-

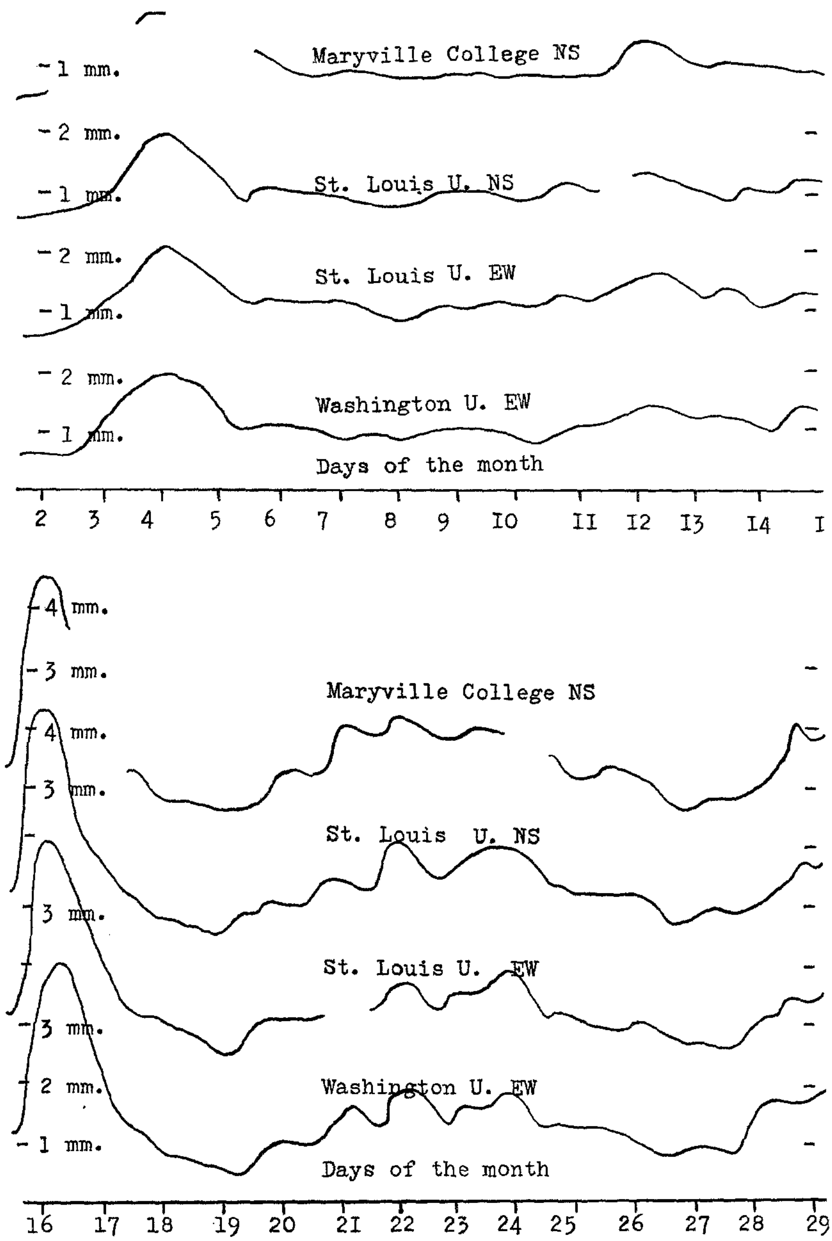


Fig. 14. Amplitude of microseisms at the three stations in St. Louis, August, 1938. Each curve has been displaced by an equal amount. This upward displacement is 2 mm. for each succeeding curve, so that the maximum displacement, at Maryville, for example, is 4.5 mm.

TABLE 1

Frequency of Amplitudes for July, 1938
(Number of occurrences during the month)

Amplitudes (mm.)	N-S		E-W	
	Maryville College	St. Louis U.	St. Louis U.	Washington U.
0.2	12	23	57	60
0.3	100	190	137	209
0.4	172	279	201	271
0.5	126	136	177	88
0.6	21	26	45	15
0.7	4	8	11	3
0.8	16	11	1	3
0.9	14	5	1	0
1.0	5	1	0	3
1.1	2	0	1	1
1.2	4	1	0	1
1.3	3	1	0	0

TABLE 2

Frequency of Amplitudes for August, 1938
(Number of occurrences during the month)

Amplitudes (mm.)	N-S		E-W	
	Maryville College	St. Louis U.	St. Louis U.	Washington U.
0.2	7	19	12	16
0.3	27	54	62	49
0.4	81	129	88	112
0.5	104	138	156	163
0.6	87	102	174	135
0.7	50	59	84	88
0.8	24	38	42	52
0.9	13	22	14	15
1.0	35	26	16	15
1.1	3	3	3	7
1.2	13	6	1	5
1.3	2	0	0	3
1.4	1	0	1	2
1.5	2	1	0	0
1.6	2	2	1	1
1.7	0	1	1	1
1.8	2	0	2	3
1.9	0	1	3	0
2.0	1	2	2	3
2.1	1	3	2	1
2.2	1	1	1	1

ing month. The frequency of occurrence of the respective amplitudes for September is shown in table 3.

October, 1938: October brought still stronger microseismic activity. The average amplitude for the month is about 1.0 mm. In the beginning of the month there were two long storms, probably a combination of several storms in succession. In the second part of the month, October 25–28, there were recorded the strongest microseisms for the entire second half of 1938.

TABLE 3

Frequency of Amplitudes for September, 1938
(Number of occurrences during the month)

Amplitudes (mm.)	N-S		E-W	
	Maryville College	St. Louis U.	St. Louis U.	Washington U.
0.2	6	17	17	7
0.3	14	21	33	27
0.4	25	57	42	39
0.5	86	116	163	134
0.6	131	154	127	154
0.7	60	56	54	84
0.8	41	38	27	26
0.9	24	20	23	25
1.0	28	30	41	35
1.1	7	8	12	6
1.2	18	14	23	19
1.3	4	3	2	5
1.4	6	12	2	5
1.5	1	2	3	5
1.6	3	8	7	6
1.7	2	1	3	6
1.8	8	7	6	10
1.9	0	1	0	2
2.0	8	4	3	9
2.1–3.0	14	20	15	23
3.1–4.0	11	8	11	9
4.1–5.0	9	8	6	9
5.1–8.0	14	10	10	14

November, 1938: November was, as a whole, even more active than the preceding month, with at least six well-distinguishable storms, namely, of November 3–6, 10–12, 15–18, 21–22, 25–28, and 28–29. The average trace amplitude is about 1.2 mm.

December, 1938: The microseismic activity for December, as far as can be seen for the first part of the month, was the strongest of all, with a probable average trace amplitude of about 1.6 mm. (See fig. 18.)

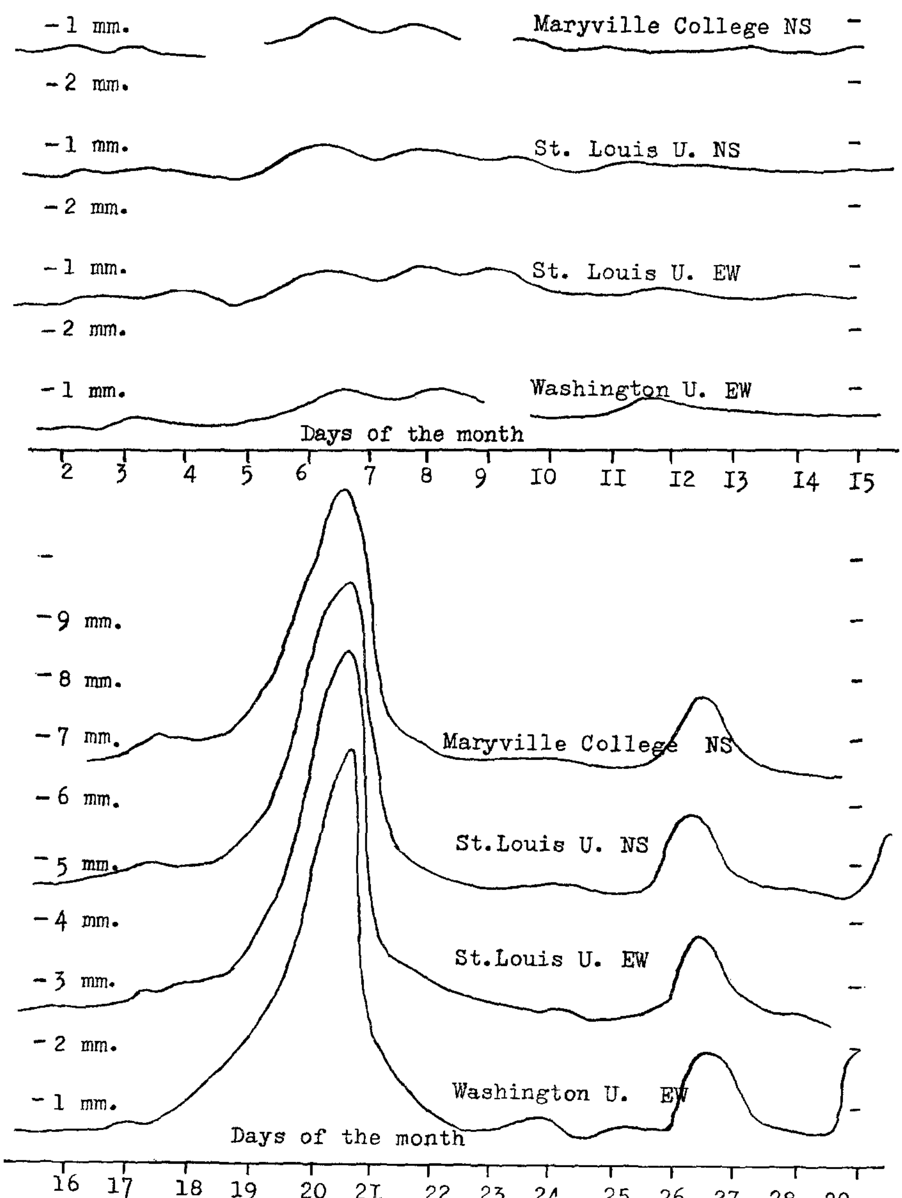


Fig. 15. Amplitude of microseisms at the three stations in St. Louis, September, 1938. Each curve has been displaced by an equal amount.

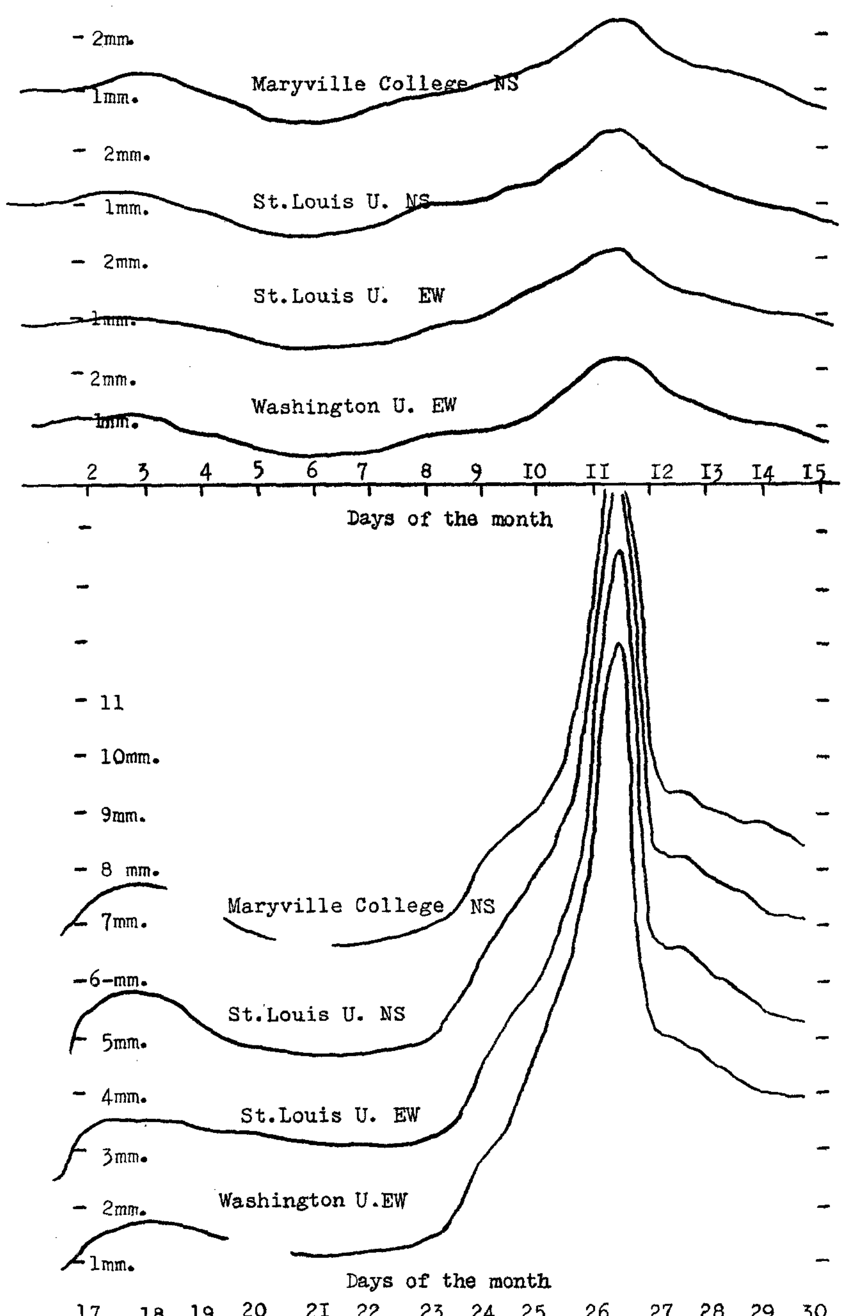


Fig. 16. Amplitude of microseisms at the three stations in St. Louis, October, 1938. Each curve has been displaced by an equal amount.

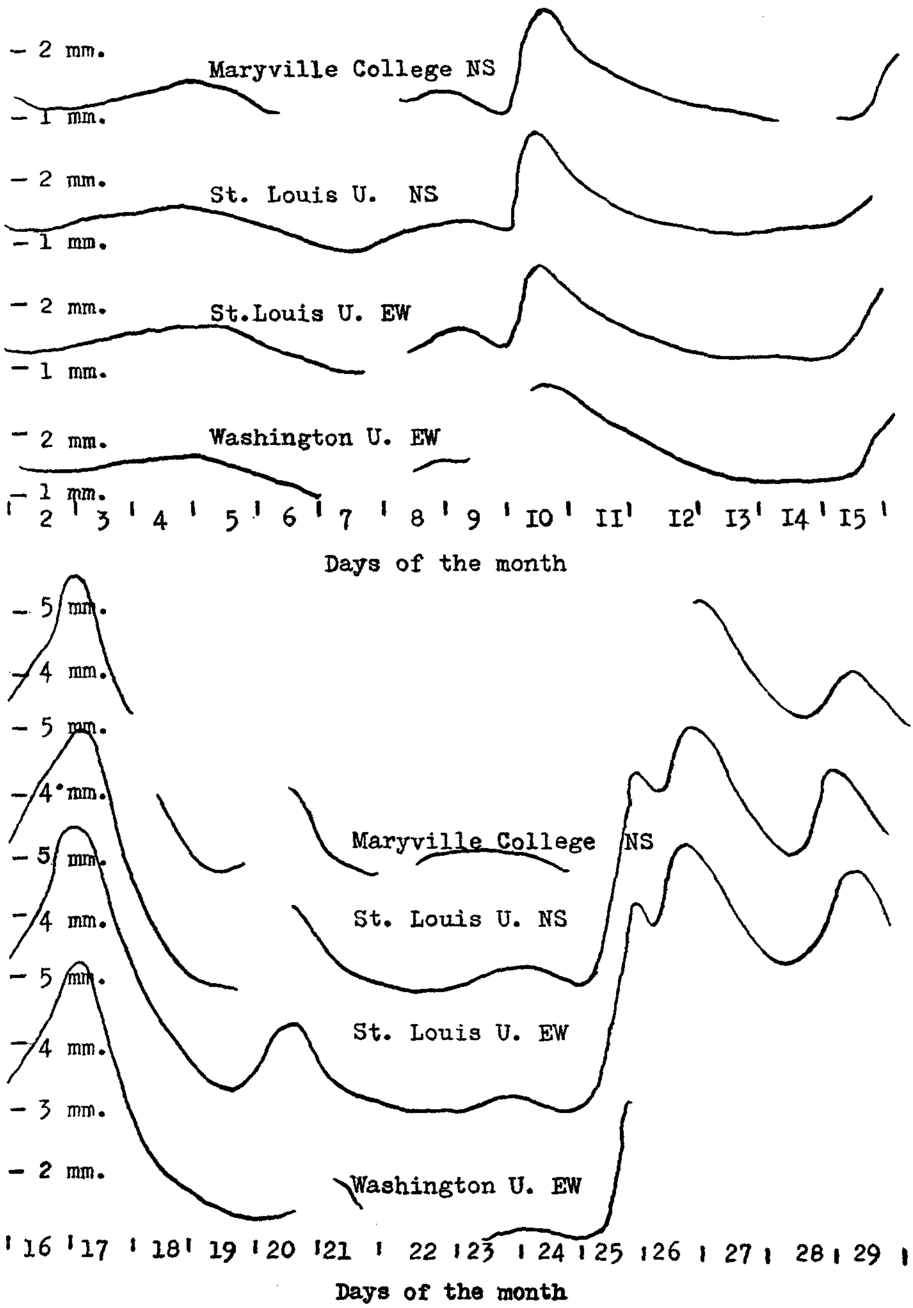


Fig. 17. Amplitude of microseisms at the three stations in St. Louis, November, 1938. Each curve has been displaced by an equal amount.

The curves of the amplitudes for the six months studied, and the tabulated frequency for the first three months indicate:

1. That this continuous restless state of the earth decreases considerably in July and August, and if we may judge from the records of the Florissant and St. Louis stations over a period of two years, the minimum amplitude corresponds to the month of July.

2. The "high fever" of the earth, to use Lacoste's term, occurs in the winter

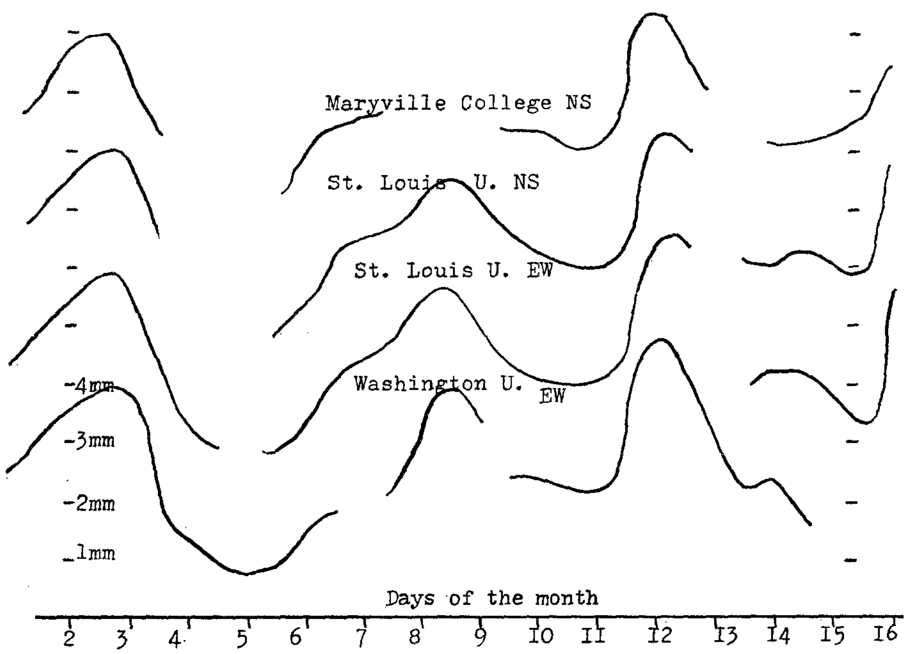


Fig. 18. Amplitude of microseisms at the three stations in St. Louis, December, 1938. Each curve has been displaced by an equal amount.

months. Our December record shows the largest average amplitude, and judging from the records mentioned above, the high peak would correspond to February.

3. A comparison of the amplitudes at St. Louis during the second part of 1938 with the sixteen-year average microseismic curve constructed by Lacoste for Strasbourg shows a rather close resemblance in the shape but not in the absolute values, the amplitudes of microseisms at St. Louis being much smaller.

4. The difference between the mean amplitudes of the N–S and E–W components is negligible. This does not mean, however, that there is always a correspondence between the maxima waves on the two components. Rather, such correspondence was found not to exist, nor was the actual relationship found to be governed by any well-defined laws.

Periods.—The periods of microseisms at St. Louis did not fluctuate very much during the six months under investigation. Figure 19 shows the period curve for July, 1938, with a more or less constant period of four seconds. The most frequent period for December was 5.2 sec. The results for July, August, and September are given both in tabulated and in diagrammatic form, according to the different components. In general, no difference was found between the periods of the same components.

In figures 20 and 21, microseisms have been arranged horizontally in groups each differing by 0.2 sec. from the preceding group, and vertically according to

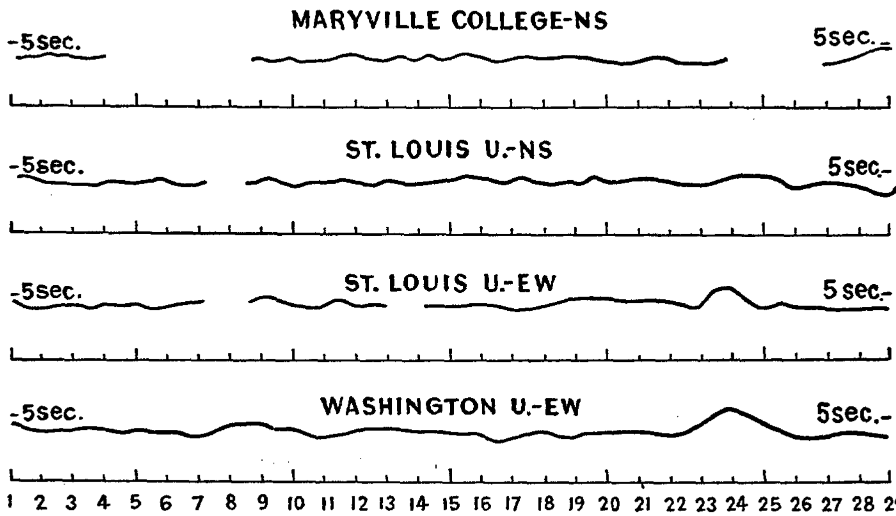


Fig. 19. Period of microseisms at the three stations in St. Louis, July, 1938.

their frequency or the number of times that each period was measured in the twenty-four daily observations, except during hours of local disturbances or during earthquakes.

In general, there are two larger groups of periods that seem to predominate: a shorter period between 3.9 and 4.1 sec. for the summer months, and a group between 4.0 and 5.5 sec. for the winter months. The frequency of the periods follows a law similar to that for the frequency of the amplitudes; in other words, there is a steady increase in the frequency of the amplitudes of microseisms as the frequency of the periods rises. To the period group of from 3.9 to 4.0 sec., which is of the highest frequency for July, there corresponds an amplitude of 0.4 mm. for the same month. During August, the frequency of periods longer than the 3.9–4.0 period group increased considerably and the highest frequency amplitude was 0.5 mm. instead of 0.4 mm.

Although it may safely be stated that there is, generally, an increase in the

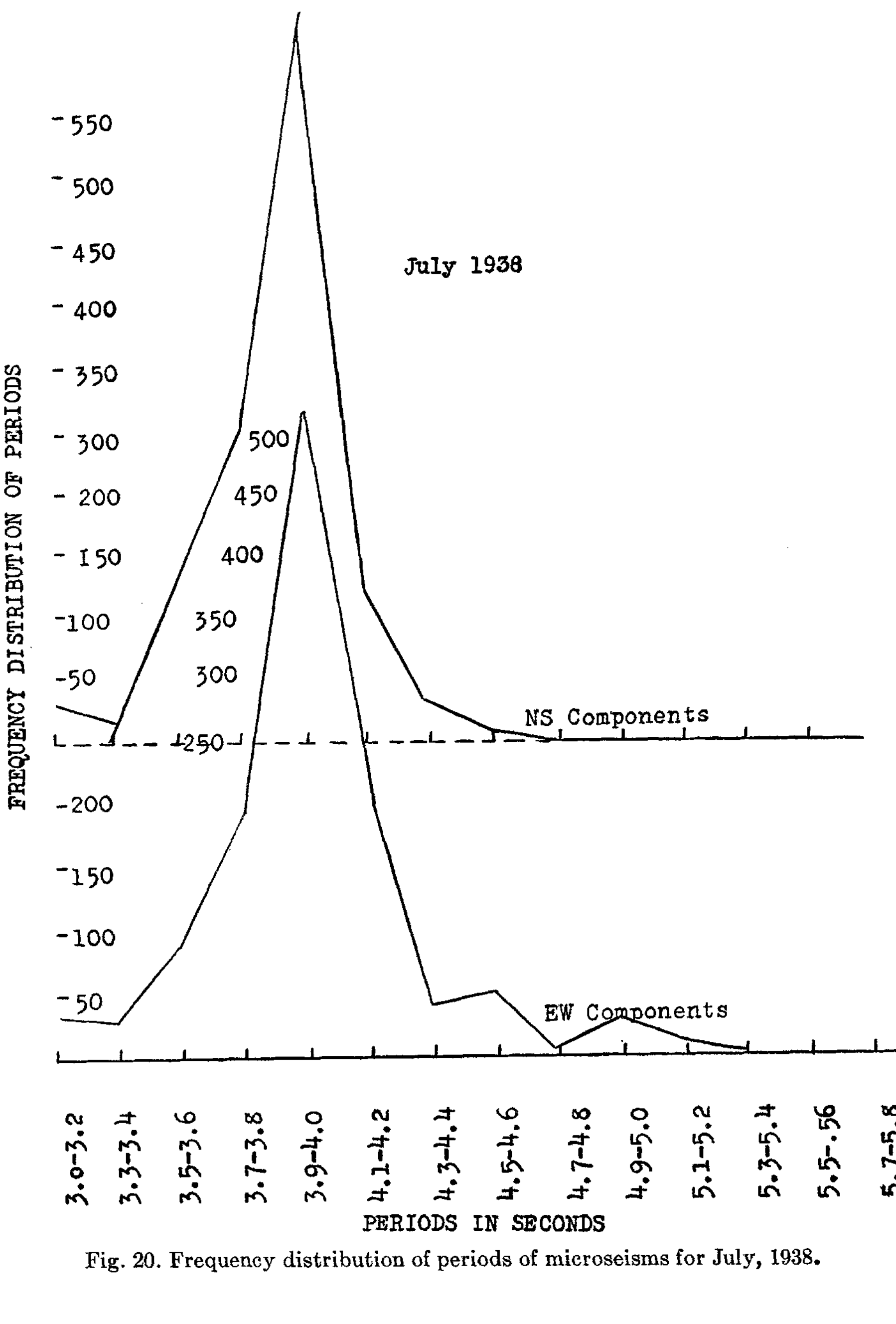


Fig. 20. Frequency distribution of periods of microseisms for July, 1938.

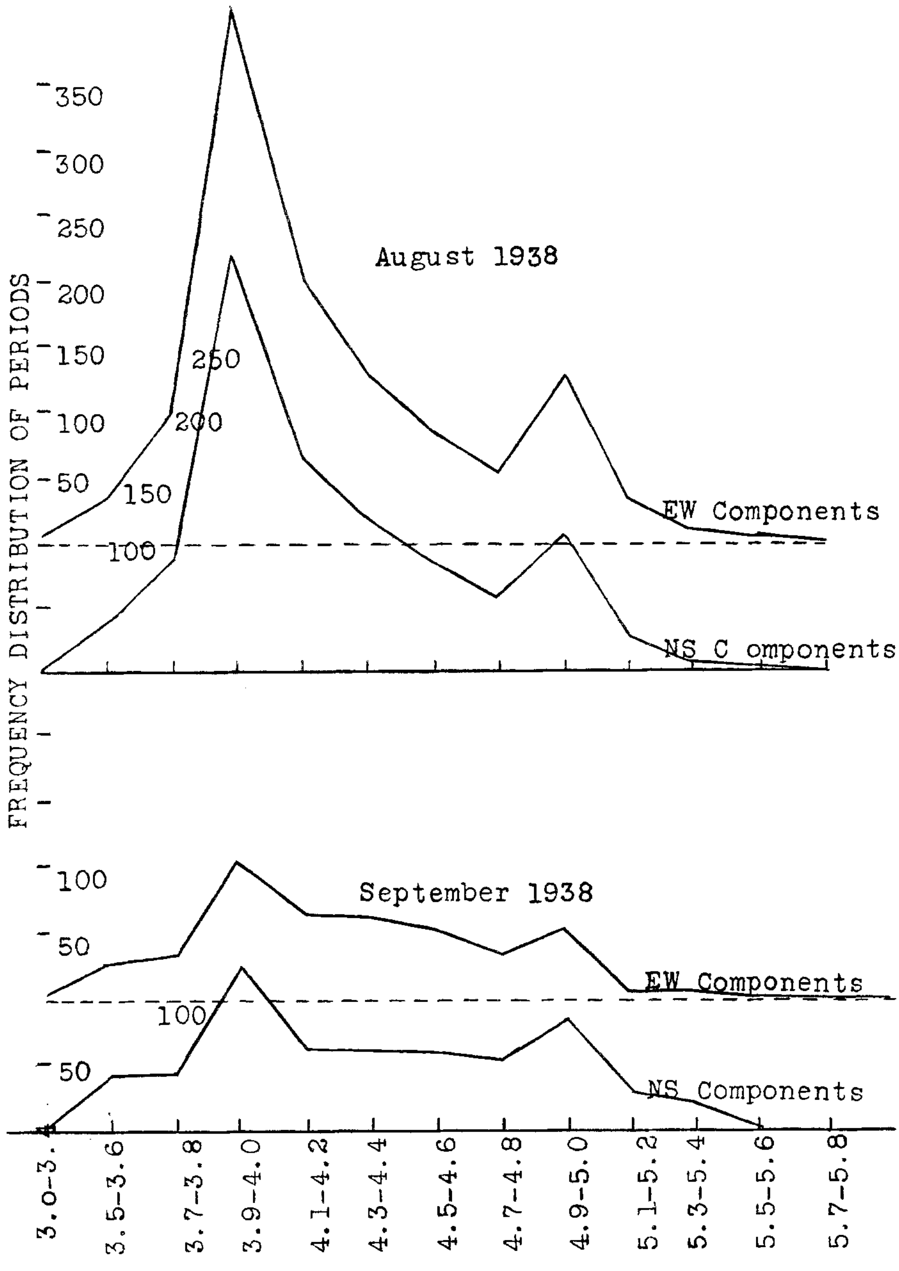


Fig. 21. Frequency distribution of periods of microseisms for August and September, 1938. (About twenty-four observations daily.)

mean amplitude of microseismic storms as the mean period lengthens, it is by no means true that for each large microseismic wave there is a corresponding long period. The opposite seems often to be true: note, for example, the storm of October 26, 1938. (See figs. 27, 28.)

The readings of the amplitudes and their corresponding periods, as measured from the original records, are given in table 4. In general, the amplitude of the

TABLE 4

Record of October 26, 1938

Break no.*	St. Louis University		Washington University	
	Amplitude	Period	Amplitude	Period
	mm.	s.	mm.	s.
2	3.5	5.0	4.0	5.3
5	4.2	5.9	3.5	6.2
6	5.0	5.8	3.0	6.9
7	3.5	6.2	3.2	5.2
8	4.0	5.0	6.0	5.0
9	10.0	5.1	7.5	5.4
10	11.2	5.1	5.5	6.4
11	6.0	6.3	2.5	6.3
12	6.0	5.4	7.0	6.0
13	4.0	5.1	7.5	6.0
14	3.0	5.0	3.0	6.2
17	3.0	5.3	1.2	4.5
26	2.5	4.9	4.0	1.5
27	2.5	5.7	2.0	5.8
32	3.0	5.2	3.0	5.5
33	5.0	5.2	2.0	5.0

* Numbers in this column refer to the numbers in figures 22 and 23.

waves seems to depend upon the intensity of the storm, and the period upon the proximity of the station to the source or origin of the waves, as will be observed later.

Propagation of Microseismic Waves

That microseisms at St. Louis are traveling waves is evidenced by every regular wave of the microseismic storms recorded there in the second part of 1938 by the four seismographs already described; and the fact is confirmed by observations made at other stations. From thousands of readings taken from the records it is evident that there exists a definite relationship between the arrival times of each wave at the different stations; that is, the troughs and crests of the waves, in the course of a storm, pass first through a certain station, and then arrive at a second station, and finally at a third station. This recording of the arrival of waves at one station ahead of another station is not simply a question of a high percentage; for regular waves of well-defined storms it is 100 per cent.

Let us take, for example, figures 22 and 23, which will give a very fair idea of the microseismic storm of October 26, 1938. These photographs of the original E–W records bring out the fact that on this date all the regular waves were arriving at the St. Louis University station earlier than at Washington University. The microseisms were coming from the northeast, and the distance between the stations is 6.4 km.

It is to be noticed that although the speed of the paper is the same at the

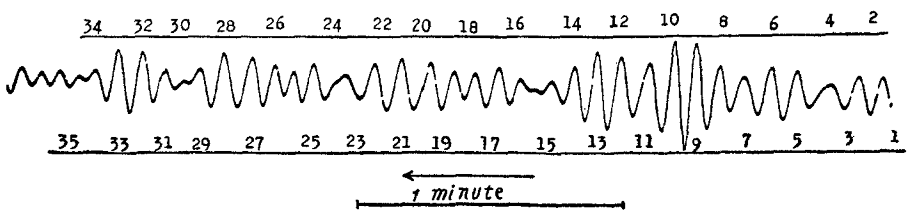


Fig. 22. Microseismic waves, E–W component, St. Louis University, October 26, 1938. Time: 2:56 to 2:59 P.M.

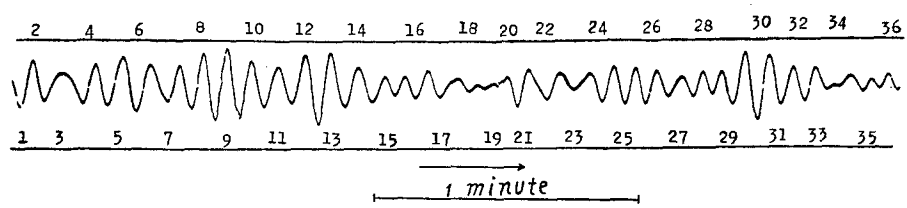


Fig. 23. Microseismic waves, E–W component, Washington University, October 26, 1938. Time: 2:56 to 2:59 P.M.

two components, the direction of rotation of the drums is opposite and consequently the lines run in opposite directions—as indicated by the arrows. The corresponding breaks caused by the tickler and the clock are numbered from 1 to 36 on both sides of the lines. The minute breaks are longer and correspond to the numbers 30, 20, and the break between 9 and 10 which was not numbered on either record.

The breaks appear sometimes as dots on top of the lines. This happens when the light beam does not move very fast over the photographic paper. It can be seen in the photographs that the distance—that is, the time—between a break and the next trough or crest is always less in the St. Louis University E–W component than it is in the Washington University E–W component. This interval may vary within certain limits, but is always positive. (See table 5.)

The variation in the interval can be accounted for as due to one factor or to several combined. There certainly is an unavoidable error in estimating tenths of a millimeter; and this will be so, no matter how good the millimeter scale, the records, and the eyes of the observer may be. The variation may also be due to other microseismic waves, of smaller amplitudes, coming from various directions and overridden by the larger waves. This interference of waves is evident in certain double or superposed storms of different directions and more

TABLE 5

ARRIVAL OF MICROSEISMIC WAVES AT ST. LOUIS UNIVERSITY AND WASHINGTON UNIVERSITY STATIONS, E–W COMPONENTS, OCTOBER 26, 2:56–2:59 P.M., 1938

Break no.	St. Louis University trough or crest-to-break interval	Washington University trough or crest-to-break interval	Difference
	s.	s.	s.
1	0.4	0.1	0.3
2	4.3	3.0	1.3
5	2.2	1.4	0.8
6	2.3	1.4	0.9
7	2.4	0.7	1.7
8	2.1	1.3	0.8
9	3.2	2.4	0.8
10	3.7	2.6	1.1
11	4.4	3.2	1.2
12	3.7	2.8	0.9
13	3.5	2.4	1.1
14	4.5	2.5	2.0
16	4.0	3.7	0.3
17	5.0	3.7	1.3
18	−0.6	1.4	2.0
23	5.2	3.6	1.6
25	5.0	4.6	0.4
26	1.7	0.8	0.9
27	3.5	1.8	1.7
28	3.4	1.9	1.5
30	0.6	−0.5	1.1
32	1.7	0.5	1.2
33	2.4	1.0	1.4

or less equal amplitudes. Finally, the variation may be due to a rather extensive area as source of origin. The focus or origin of microseisms does not seem to be a point, as is the first motion in earthquakes, but rather a region several hundred kilometers in diameter.

It has been found that the average value of the varying differences of arrival of waves at the two stations is approximately the same, namely, ±0.2 sec. for groups of readings of ten each.

A relationship of arrival times similar to that shown here between the two

E–W components exists also between the N–S components of St. Louis University and Maryville College. In the case cited, St. Louis University is always ahead of Maryville.

Furthermore, it has been possible to identify on the records of the seismographs of the Florissant station the traveling waves that passed through St. Louis a few seconds before or after, as the case may be. Occasions were considered upon which the direction of microseisms was known and the exact time on the records was well established, as when United States Naval Observatory

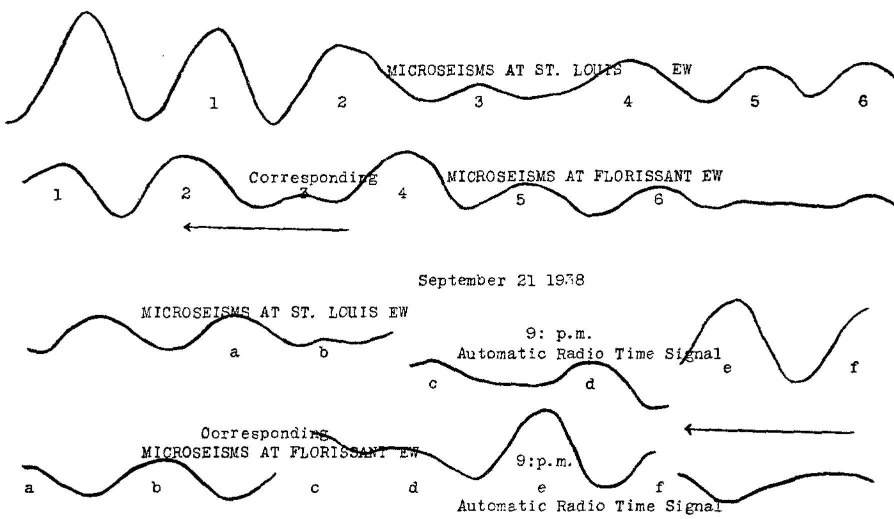


Fig. 24. Enlargement of microseismic waves at two stations 21.8 km. apart. Microseisms are coming from the east, and the time difference on arrival is about 4 sec. or 6 cm.

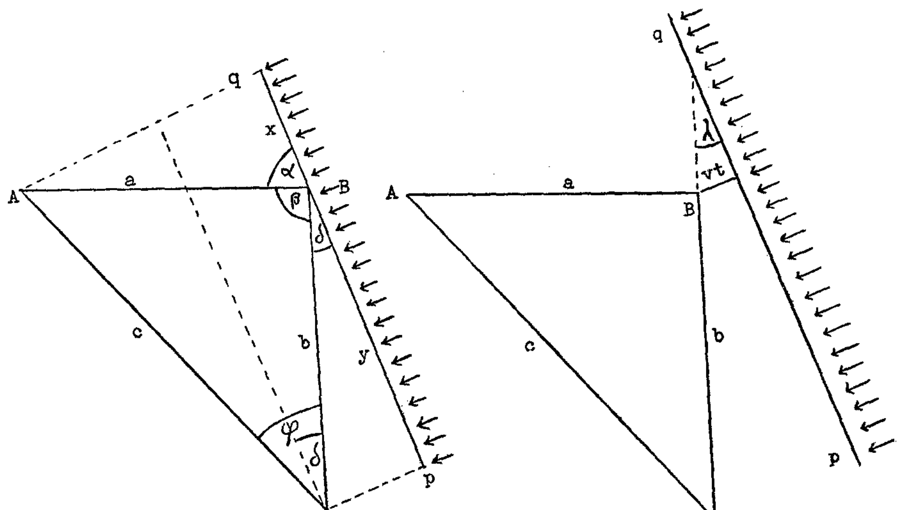
radio time signals from Arlington were automatically recorded on the records of Florissant and St. Louis. The distance between the two stations is 21.8 km.

On September 21, 1938, microseisms were coming toward St. Louis from the east. The storm had subsided greatly at 9:00 P.M., local time, but the waves were large enough to be identified at the two stations. The time signals from Arlington were registered on the records for about four minutes. Figure 24 shows the waves at the two stations, magnified by projecting them on a screen and tracing them under each other for the purpose of identification. The time is the fifty-ninth minute after 8:00 P.M., September 21, and the break in the line is the 9-o'clock signal. From the corresponding crests numbered successively, one can see that the same type and number of waves seem to have passed St. Louis first and then reached Florissant some four seconds later, as expected.

We take this similarity of shape and number at the calculated time and at such a distance as the effect of an evenly propagated wave movement, and as a consequence we speak of a wave path or direction *D*, of a travel time *t*, of a velocity v, and of a wave length λ. (The rest of this section will be a further confirmation of the statement that microseismic waves are not stationary waves, but rather traveling waves.)

Direction of propagation.—The direction of arrival of microseismic waves at St. Louis can be obtained from the layout of the network of stations, either by analysis or by construction.

Let, for example, a, b, and c in figure 25 be the distances between the stations A, B, and C, which represent Washington University, St. Louis University, and Maryville College, respectively.



Figs. 25 and 26. Layout of the stations, in the form of a triangle; figure 25 for the calculation of the direction of microseisms, figure 26 for the calculation of the velocity of microseisms.

Let α and δ be the angles which a and b make with the wave front of microseisms.

Let the projections of a and b on the wave front be x and y. Then we obtain the relations:

$$\cos\delta = \frac{y}{b} \qquad \cos\alpha = \frac{x}{a}$$

$$\frac{x}{y} = \frac{t_2}{t_1} \qquad \alpha+\beta+\delta = 180°$$

t_1 being the difference of arrival times of the corresponding crests or troughs at stations A and B, and t_2 at stations B and C.

Also, we can write

$$\cos \alpha = \frac{\frac{t_2}{t_1} \cdot b \cos \delta}{a}$$

Making

$$k = \frac{t_2\, b}{t_1\, a}$$

$$\cos \alpha = k \cos \delta$$

But

$$\cos \delta = -\cos(\beta + \alpha)$$

Therefore

$$\cos \alpha = -k \cos(\beta + \alpha)$$

Expanding,

$$\cos \alpha = -k(\cos \alpha \cos \beta - \sin \alpha \sin \beta)$$

or

$$\cos \alpha (1 + k \cos \beta) = k \sin \alpha \sin \beta$$

Whence

$$\tan \alpha = \frac{1 + k \cos \beta}{k \sin \beta}.$$

From the value of the tangent α the direction of propagation of the microseisms can be readily obtained, since the direction of a is known.

The constructional way of determining the direction consists in adjusting the position of the ray or the angles α and δ (fig. 25) in such a manner that the velocity of the waves along qA is equal to the velocity of the waves along pC; in other words, since $\mathrm{qA} = vt_1$ and $\mathrm{Cp} = vt_2$,

$$\frac{\mathrm{qA}}{t_1} = v = \frac{\mathrm{Cp}}{t_2}$$

Constructing the triangles AqB and BpC, with Aq and Bp perpendicular to the wave front qp, and Aq and Bp distances as obtained from the equations given above, we can find the angles α and δ and thus the direction of propagation of microseisms.

Velocity.—The calculation of the velocity of microseisms is closely connected with the calculation of the direction, which latter is found at once from the angle. If the direction of microseisms is known and the velocity is assumed to be uniform, it will be given by $v = \dfrac{\mathrm{Aq}}{t_1} = \dfrac{\mathrm{Cp}}{t_2}$.

The velocity of microseismic waves can also be found directly from the following known formula:

$$v = \frac{\pm(x_1 y_2 - x_2 y_1)}{\sqrt{(t_2 x_1 - t_1 x_2)^2 + (t_2 y_1 - t_1 y_2)^2}}$$

where the coördinates of the three stations A, B, and C are x_1, y_1, 0, 0, and x_2, y_2, respectively.

This formula can be derived from a consideration of the layout of the stations by means of the Cartesian coördinates. Let the zero point of the system of coördinates be the St. Louis University station or B (fig. 26), and let the Y ordinate be in the N–S direction, and the X abscissa be in the E–W direction. Let the wave front be represented by qp. Let the acute angle between the Y ordinate and the wave front be λ; then, when vt is the distance between the center of coördinates and the wave front, the equation of the wave front is:

$$x \cos \lambda + y \sin \lambda = vt \tag{1}$$

At $x_1 y_1 t_1$, the equation is

$$x_1 \cos \lambda + y_1 \sin \lambda = vt_1$$

At $x_2 y_2 t_2$, the equation is

$$x_2 \cos \lambda + y_2 \sin \lambda = vt_2$$

Eliminating v from these equations we obtain:

$$\cos \lambda (t_2 x_1 - t_1 x_2) + \sin \lambda (t_2 y_1 - t_1 y_2) = 0$$

or

$$\tan \lambda = -\frac{t_2 x_1 - t_1 x_2}{t_2 y_1 - t_1 y_2}$$

Now,

$$\cos \lambda = \frac{1}{\pm\sqrt{1+\tan^2 \lambda}} \quad \text{or} \quad = \frac{(t_2 y_1 - t_1 y_2)^2}{\pm\sqrt{(t_2 y_1 - t_1 y_2)^2 + (t_2 x_1 - t_1 x_2)^2}}$$

also

$$\sin \lambda = \frac{1}{\csc \lambda} = \frac{1}{\pm\sqrt{1+\cot^2 \lambda}} \quad \text{or} \quad = \frac{(t_2 x_1 - t_1 x_2)^2}{\pm\sqrt{(t_2 x_1 - t_1 x_2)^2 + (t_2 y_1 - t_1 y_2)^2}}$$

If we take $\cos \lambda$ with $\pm$, then the $\sin \lambda$ must be taken with $\mp$ in order that the tangent $\lambda = \dfrac{\sin \lambda}{\cos \lambda}$ be $-\dfrac{t_2 x_1 - t_1 x_2}{t_2 y_1 - t_1 y_2}$.

Substituting the values of $\sin \lambda$ and $\cos \lambda$ in eq. (1) and considering the point x_1 y_1, and t_1, we have

$$\frac{x_1(t_2 y_1 - t_1 y_2) \;-\; (t_2 x_1 - t_1 x_2)}{\pm\sqrt{(t_2 x_1 - t_1 x_2)^2 + (t_2 y_1 - t_1 y_2)^2}} = vt_1$$

Removing parentheses in the numerator and combining,

$$\frac{-\, t_1 x_1 y_2 + y_1 x_2 t_1}{\pm\sqrt{(t_2 x_1 - t_1 x_2)^2 + (t_2 y_1 - t_1 y_2)^2}} = vt_1$$

Dividing by t_1

$$\frac{x_1y_2 - x_2y_1}{\pm\sqrt{(t_2x_1-t_1x_2)^2+(t_2y_1-t_1y_2)^2}} = v$$

The sign must be so chosen that v is positive or we take

$$+\sqrt{\ } \text{ if } x_1y_2-x_2y_1>0 \quad \text{and} \quad -\sqrt{\ } \text{ if } x_1y_2-x_2y_1<0$$

Determination of direction and velocity.—Let us now apply these methods of determining the direction and velocity of microseisms to several storms. The

TABLE 6

ARRIVAL TIMES OF MICROSEISMIC WAVES ON THE E–W COMPONENTS OF ST. LOUIS UNIVERSITY AND WASHINGTON UNIVERSITY STATIONS, OCTOBER 24, 1938

Local time	Break no.	Wave		Trough-break interval		Time difference (sec.)	Phase difference (deg.)
		Ampl. (mm.)	Per. (sec.)	St. Louis University	Washington University		
$10^h\ 1^m$	1	2.6	6.2	1.9	2.8	−0.9	52.1
	2	2.6	6.2	5.4	6.0	−0.6	34.8
	3	3.0	6.3	0.7	2.0	−1.3	74.3
	4	3.2	6.3	−0.2	0.2	−0.4	22.9
	5	2.9	6.2	−1.2	−0.6	−0.6	34.8
10^h45^m	6	2.5	7.0	1.6	1.7	−0.1	5.1
	7	2.3	6.2	2.2	2.4	−0.2	12.5
$11^h\ 2^m$	8	3.0	7.0	−1.8	−1.0	−0.8	41.1
	9	3.2	7.2	1.7	2.4	−0.7	35.0
	10	2.5	6.0	5.1	5.5	−0.4	24.0
Total sum.........		27.8	64.6	15.4	21.4	6.0	336.7
Average...........		2.8	6.5	1.5	2.1	0.6	33.7

first storm studied in detail is the one of largest amplitudes, which really includes several storms from October 23 to October 28. The next largest one is the storm of September 20–22. Another storm that will be considered here, alalthough not the next strongest in intensity, is the one of August 15–17. The direction and velocity of other storms are the same as in the ones mentioned, and the results will be given in connection with the problem of the origin of microseisms.

The strongest storm of all, with respect to ground displacement, began on October 23, 1938. The microseismic waves, some of which were to rise to amplitudes of 14 mm. on the records, started at the four stations with amplitudes of

4.0 mm. during the first two days. The amplitudes fell to a low of 3.0 mm. on the 25th between 5:00 P.M. and 8:00 P.M., local time, and reached an average maximum above 10.0 mm. about noon, October 26. After that the amplitudes decreased very rapidly, so that for the midnight of the 27th they were 4.0 mm., and on the 28th they reached the 1.4-mm. line (fig. 27). A series of ten readings

TABLE 7

ARRIVAL TIMES OF MICROSEISMIC WAVES ON THE N–S COMPONENTS OF ST. LOUIS UNIVERSITY AND MARYVILLE COLLEGE STATIONS, OCTOBER 24, 1938

Local time	Break no.	Wave		Trough-break interval		Time difference (sec.)	Phase difference (deg.)
		Ampl. (mm.)	Per. (sec.)	St. Louis University	Maryville College		
$10^h\ 1^m$	1	2.4	7.0	0.0	−2.1	2.1	108.0
	2	3.0	7.0	3.9	1.7	2.2	113.1
	3	4.0	7.2	3.5	1.0	2.5	125.0
	4	3.5	7.1	4.6	2.2	2.4	121.6
	5	3.6	7.0	3.6	1.0	2.6	130.3
$10^h 45^m$	6	3.0	6.3	−1.8	−4.1	2.3	131.4
	7	3.4	6.2	6.2	3.8	2.4	139.3
$11^h\ 2^m$	8	1.0	6.4	−1.8	−4.2	2.4	137.1
	9	1.4	6.5	1.8	−0.5	2.3	127.4
	10	0.9	5.5	4.9	2.5	2.4	157.1
Total sum..........		26.2	66.2	24.9	1.3	23.6	1290.3
Average...........		2.6	6.6	2.49	0.13	2.36	129.0

taken October 24 at $10^h\ 1^m$, $10^h\ 45^m$, and $11^h\ 2^m$ are presented in tables 6 and 7.

The average time difference between St. Louis University and Washington University is 0.6 sec., and the average time difference between St. Louis University and Maryville College is 2.36 sec. These time differences give definitely a direction of microseismic waves from N 8° W. The direction of the microseismic wave front is shown in figure 29. The distance, travel time, and velocity of microseismic waves are also indicated in diagrammatic form in figure 30. The velocity obtained by the methods described was between 2.65 and 2.64 km/sec.

A few other readings taken from the records of the 24th and particularly of the 25th seem to indicate another storm with a general N 45° W direction, corresponding to a difference of arrival time between St. Louis and Maryville of about 1.4 sec., but readings could not be taken in numbers sufficient to warrant a definite conclusion.

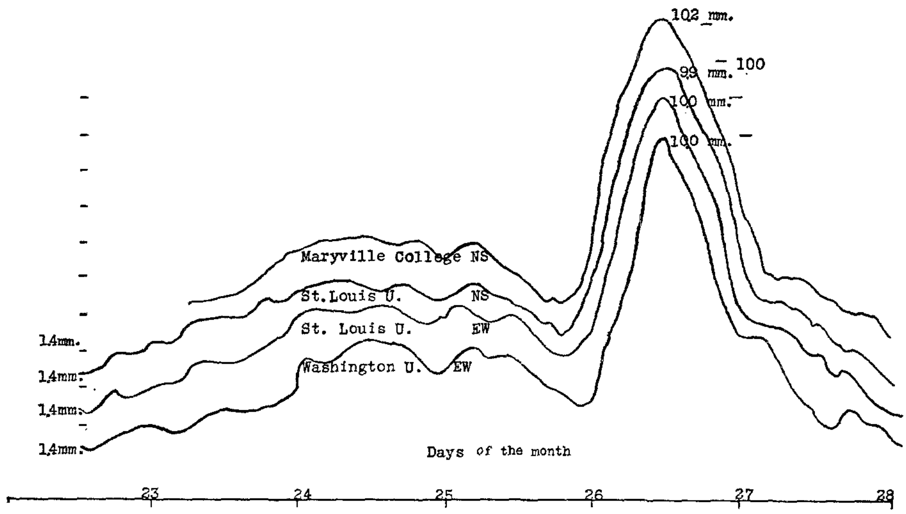


Fig. 27. Microseismic storm, October 23–28, 1938. Amplitudes in mm. Scales displaced 10 mm.

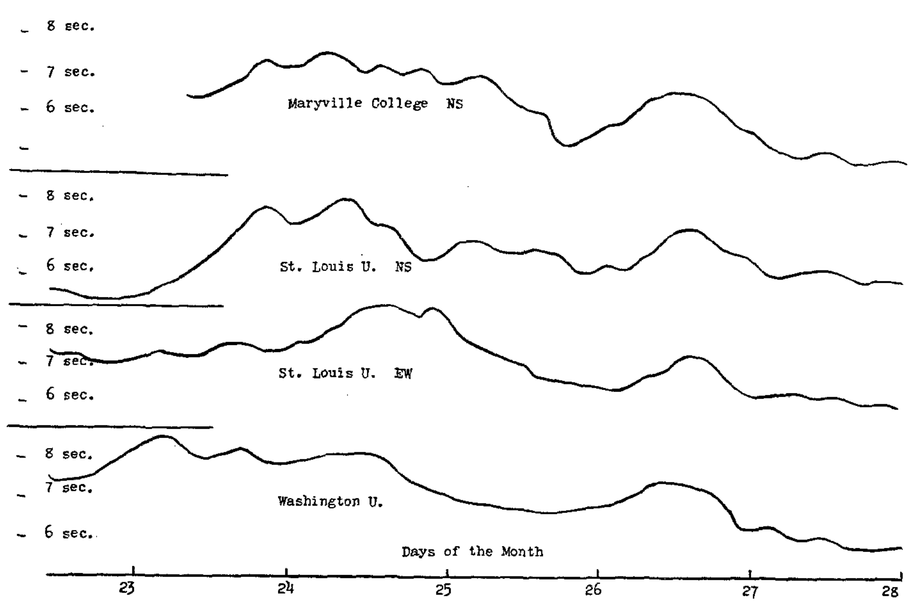


Fig. 28. Microseismic storm, October 23–28, 1938. Periods of microseismic waves, in seconds.

On October 26, a total of one hundred and thirty trough-to-break intervals were measured from the records of the E–W components, together with the period and amplitude of each wave for the period between 2:45 and 3:15 P.M., local time, and fifty such measurements were made from the records of the N–S components, for the period between 2:45 and 3:45 P.M., local time. Arrange-

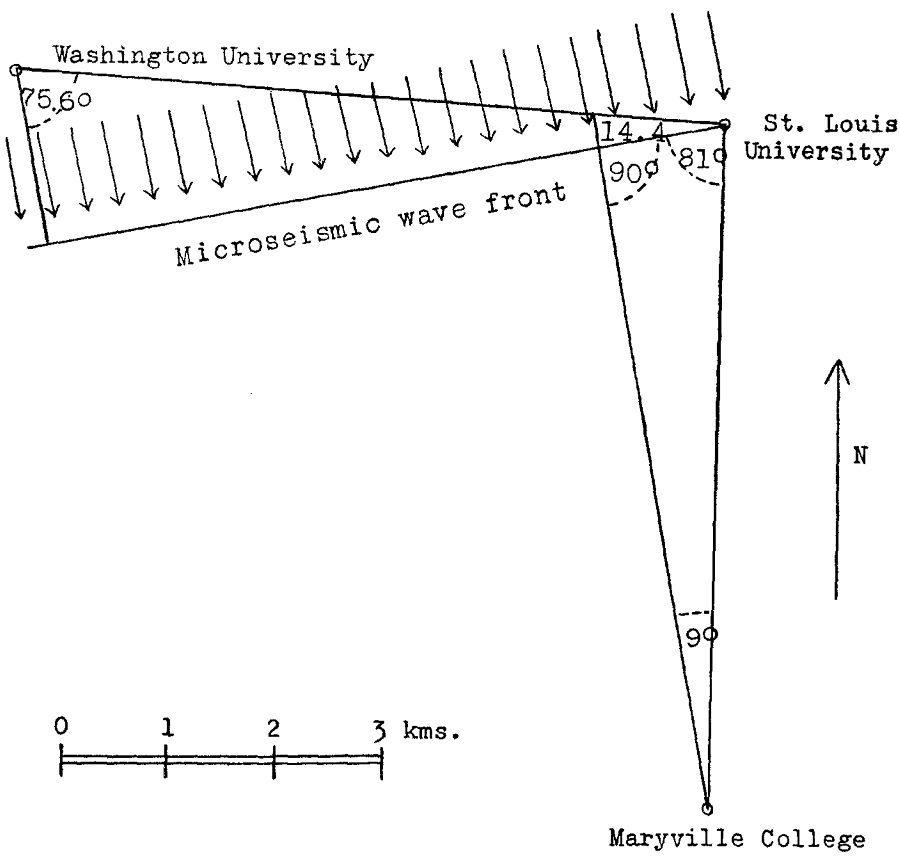


Fig. 29. Direction of microseismic waves at St. Louis, October 24, 1938: N 8° W.

ments were made during this particular hour to record only two lines of microseisms of fifteen minutes' duration on each record. In the N–S Maryville records the 6-sec. breaks were somewhat obscured by the strong light of the line and only the longer minute marks of the line were clearly distinguishable.

Of many readings taken, some had to be discarded because of irregularities in the line or because of local disturbances; the rest are given here in the form of two tables (tables 8 and 9) divided into groups of ten or fewer, with the total sum and the average for each group. The first four groups of the E–W components are made up of all readings of waves whose character was regarded as regular sinusoidal. The fifth, sixth, and seventh groups are of waves of less regular form.

There are three groups of readings for the N–S component; the first is made

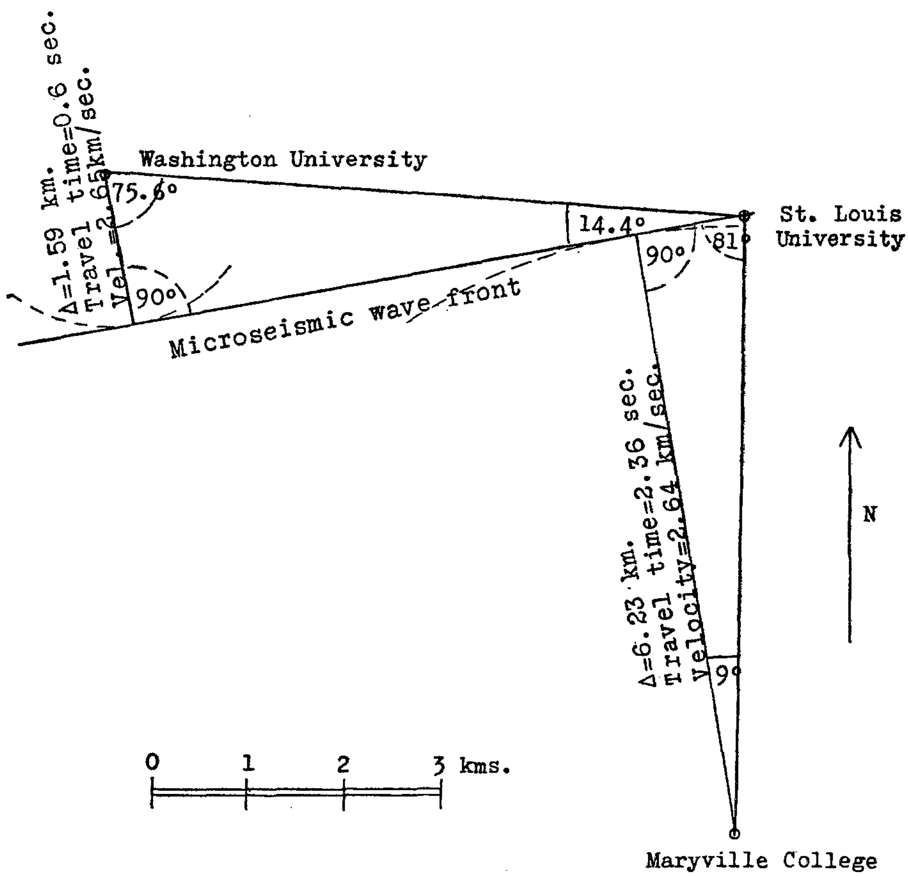


Fig. 30. Velocity of microseismic waves from N 8° W at St. Louis, October 24, 1938.

up of readings from regular sinusoidal waves, and the second and third from less regular waves.

Table 10 shows that the averages are about the same for the two classes of waves.

As table 10 shows, the average of the various group averages for the first pair of stations of St. Louis University and Washington University was 1.15 sec., made up of values as low as 0.86 sec. and as high as 1.28 sec., which represents a difference between maximum and minimum values of only 0.42 sec.

TABLE 8

ARRIVAL TIME OF MICROSEISMIC WAVES AT ST. LOUIS UNIVERSITY AND WASHINGTON UNIVERSITY STATIONS ON THE E–W COMPONENTS, OCTOBER 26, 1938, BETWEEN 2:45 AND 3:15 P.M. (LOCAL TIME)

(Selected readings of regular sinusoidal waves—first to fourth groups—and of less regular waves—fifth to seventh groups—as recorded at the two stations)

Break no.	St. Louis University			Washington University			Difference	
	Wave		Trough-to-break interval (sec.)	Wave		Trough-to-break interval (sec.)	Time (sec.)	Phase (deg.)
	Ampl. (mm.)	Per. (sec.)		Ampl. (mm.)	Per. (sec.)			
FIRST GROUP								
a 19	5.8	4.0	0.8	5.0	5.6	−0.8	1.6	99.0
a 20	6.0	6.0	0.7	5.2	5.6	−0.2	0.9	56.0
a 21	5.2	5.4	1.2	2.5	5.0	0.3	0.9	54.0
a 26	2.5	5.8	3.9	3.5	6.1	2.4	1.5	91.5
a 40	7.0	6.4	2.5	6.5	6.0	1.6	0.9	52.5
a 45	2.0	5.2	1.7	1.8	5.0	0.4	1.3	93.5
a 49	3.3	5.3	4.2	2.2	5.4	3.0	1.2	80.5
a 50	4.0	5.1	4.9	4.0	5.4	3.7	1.2	81.0
a 51	5.2	5.0	5.0	5.0	60.	4.0	1.0	65.3
a 53	2.2	5.4	3.0	3.8	5.2	2.1	0.9	62.0
Total	43.2	56.6	27.9	39.5	55.0	16.5	11.4	735.3
Average	4.3	5.7	2.8	3.9	5.5	1.65	1.14	73.5
SECOND GROUP								
2	3.5	5.0	4.3	4.0	5.3	3.0	1.3	91.5
5	4.2	5.9	2.2	3.5	6.2	1.4	0.8	47.5
6	5.0	5.8	2.3	3.0	6.9	1.4	0.9	51.5
7	3.5	6.2	2.4	3.2	5.2	0.7	1.7	111.0
8	4.0	5.0	2.1	6.0	5.0	1.3	0.8	57.5
9	10.0	5.1	3.2	7.5	5.4	2.4	0.8	55.5
10	11.2	5.1	3.7	5.5	6.4	2.6	1.1	61.0
11	6.0	6.3	4.4	2.5	6.3	3.2	1.2	84.3
12	6.0	5.4	3.7	7.0	6.0	2.8	0.9	57.0
13	4.0	5.1	3.5	7.5	6.0	2.4	1.1	72.0
Total	57.4	54.9	31.8	49.7	58.7	21.2	10.6	678.8
Average	5.74	5.49	3.18	4.97	5.87	2.12	1.06	67.88

TABLE 8—(*Continued*)

Break no.	St. Louis University			Washington University			Difference	
	Wave		Trough-to-break interval (sec.)	Wave		Trough-to-break interval (sec.)	Time (sec.)	Phase (deg.)
	Ampl. (mm.)	Per. (sec.)		Ampl. (mm.)	Per. (sec.)			
THIRD GROUP								
14	3.0	5.0	4.5	3.0	6.2	2.5	2.0	130.0
17	3.0	5.3	5.0	1.2	4.5	3.7	1.3	88.0
26	2.5	4.9	1.7	4.0	1.5	0.8	0.9	63.0
27	2.5	5.7	3.5	2.0	5.8	1.8	1.7	105.0
32	3.0	5.2	1.7	3.0	5.5	0.5	1.2	78.0
33	5.0	5.2	2.4	2.0	5.0	1.0	1.4	101.0
40	1.8	5.4	4.9	2.8	5.4	3.9	1.0	66.0
43	3.5	5.0	0.2	3.0	5.2	−0.7	0.9	63.0
45	11.0	5.0	4.8	7.5	5.6	4.2	0.6	40.0
50	2.5	5.0	2.0	1.8	5.4	1.1	0.9	42.0
Total	37.8	51.7	30.7	30.3	50.1	18.8	11.9	777.8
Average	3.78	5.17	3.07	3.03	5.01	1.88	1.19	77.8
FOURTH GROUP								
51	3.5	5.8	3.4	3.0	6.3	2.2	1.2	74.0
52	2.0	6.2	3.6	2.5	5.3	1.2	2.4	149.0
54	2.5	5.0	3.6	4.0	5.0	2.3	1.3	94.0
61	6.0	6.0	5.9	5.0	6.1	5.3	0.6	36.0
62	10.0	6.7	5.6	8.0	6.6	4.6	1.0	53.5
64	8.0	6.9	4.7	9.0	6.0	3.3	1.4	78.5
65	7.0	5.9	4.0	9.0	5.8	2.7	1.3	79.0
66	7.0	6.4	5.0	9.0	6.6	4.0	1.0	56.5
69	3.5	5.4	1.6	3.5	5.7	0.5	1.1	69.0
70	6.0	5.2	2.0	3.5	5.4	0.8	1.2	88.5
Total	55.5	59.5	39.4	56.5	58.8	26.9	12.6	778.0
Average	5.55	5.95	3.94	5.65	5.88	2.69	1.26	77.80

TABLE 8—(*Continued*)

Break no.	St. Louis University			Washington University			Difference	
	Wave		Trough-to-break interval (sec.)	Wave		Trough-to-break interval (sec.)	Time (sec.)	Phase (deg.)
	Ampl. (mm.)	Per. (sec.)		Ampl. (mm.)	Per. (sec.)			
FIFTH GROUP								
a 13	10.5	6.1	3.5	7.0	6.5	2.6	0.9	51.5
a 14	10.5	6.1	5.2	7.0	6.8	4.4	0.8	44.9
a 16	10.0	5.8	2.5	5.5	5.2	2.2	0.3	19.0
a 27	2.0	6.0	5.0	2.5	6.7	2.3	2.7	152.0
a 28	1.6	5.0	4.1	3.0	6.0	1.9	2.2	144.0
a 39	8.0	5.6	2.5	5.0	6.0	1.5	1.0	62.5
a 46	1.8	5.1	2.9	1.4	5.1	1.4	1.5	106.0
a 47	1.8	5.0	4.8	1.4	5.3	3.5	1.3	90.0
a 48	1.8	5.1	3.7	2.5	5.0	2.4	1.3	90.0
a 51	5.0	5.0	4.8	5.0	5.4	4.0	0.8	55.5
Total	53.0	54.8	39.0	40.3	58.0	26.2	12.8	815.4
Average	5.3	5.48	3.9	4.03	5.8	2.62	1.28	81.5
SIXTH GROUP								
a 54	3.0	5.2	3.8	1.4	6.0	3.6	0.2	12.0
1	2.0	5.3	0.4	4.0	5.3	0.1	0.3	20.5
16	2.4	5.2	4.0	1.2	5.2	3.7	0.3	20.0
18	3.0	5.2	−0.6	1.0	7.0	1.4	2.0	116.0
25	3.0	5.4	5.0	4.0	4.8	4.6	0.4	26.5
28	4.3	5.8	3.4	1.5	4.7	1.9	1.5	107.5
30	2.5	5.4	0.6	8.0	5.6	−0.5	1.1	72.0
31	2.0	5.0	2.0	7.5	5.3	1.0	1.0	69.2
44	3.5	5.0	4.0	1.5	5.0	2.8	1.2	84.0
48	1.2	5.7	3.7	3.0	5.2	3.1	0.6	42.0
Total	26.9	53.2	27.5	33.1	54.4	18.9	8.6	569.2
Average	2.69	5.32	2.75	3.31	5.44	1.89	0.86	56.9

TABLE 8—(*Concluded*)

Break no.	St. Louis University			Washington University			Difference	
	Wave		Trough-to-break interval (sec.)	Wave		Trough-to-break interval (sec.)	Time (sec.)	Phase (deg.)
	Ampl. (mm.)	Per. (sec.)		Ampl. (mm.)	Per. (sec.)			
SEVENTH GROUP								
49	2.0	5.4	5.3	2.0	5.7	4.7	0.6	38.8
53	1.8	5.7	3.2	4.3	5.3	1.7	1.5	98.0
55	2.5	5.3	4.8	1.5	5.0	3.4	1.4	97.0
56	4.3	5.2	4.3	1.4	5.4	3.5	0.8	56.5
60	3.5	6.9	6.9	2.5	6.0	5.0	1.9	110.0
67	3.0	5.2	4.1	2.0	6.1	3.5	0.6	38.5
71	7.0	6.0	2.3	4.5	5.4	0.1	2.2	139.0
Total	24.1	39.7	30.9	17.2	38.9	21.9	9.0	578.3
Average	3.44	5.67	4.41	2.46	5.56	3.12	1.28	82.6

TABLE 9

ARRIVAL TIMES OF MICROSEISMIC WAVES AT ST. LOUIS UNIVERSITY AND MARYVILLE COLLEGE STATIONS ON THE N–S COMPONENTS, OCTOBER 26, 1938, BETWEEN 2:45 AND 3:15 P.M. (LOCAL TIME)

(Readings of regular waves—first group—and of less regular waves—second and third groups—as recorded at the two stations)

Break no.	St. Louis University			Maryville College			Difference	
	Wave		Trough-to-break interval (sec.)	Wave		Trough-to-break interval (sec.)	Time (sec.)	Phase (deg.)
	Ampl. (mm.)	Per. (sec.)		Ampl. (mm.)	Per. (sec.)			
FIRST GROUP								
1	1.3	6.2	2.2	8.0	5.2	−0.1	2.3	138.0
4	0.9	5.7	4.8	5.0	5.2	2.9	1.9	110.0
6	0.9	5.3	3.0	2.5	4.8	0.8	2.2	154.0
21	1.0	5.0	4.6	6.0	6.0	2.4	2.2	132.0
30	1.3	5.1	3.7	2.5	4.9	2.0	1.7	122.0
31	1.1	5.8	5.0	2.5	5.0	3.3	1.7	121.0
34	0.7	5.4	4.4	2.8	4.7	2.3	2.1	148.0
36	1.4	6.2	3.4	6.0	5.9	1.4	2.0	122.0
37	1.3	5.8	2.1	4.0	5.5	0.0	2.1	133.0
38	1.0	5.8	0.6	4.0	6.0	−1.7	2.3	143.0
Total	10.9	56.3	33.8	43.3	53.2	13.40	20.5	1326.0
Average	1.1	5.6	3.38	4.3	5.3	1.34	2.05	132.6

TABLE 9—(*Continued*)

Break no.	St. Louis University			Maryville College			Difference	
	Wave		Trough-to-break interval (sec.)	Wave		Trough-to-break interval (sec.)	Time (sec.)	Phase (deg.)
	Ampl. (mm.)	Per. (sec.)		Ampl. (mm.)	Per. (sec.)			
SECOND GROUP								
5	1.0	5.7	0.9	5.0	7.3	−1.0	1.9	104.0
7	0.9	4.8	0.1	2.5	4.8	−1.6	1.7	128.0
8	0.9	4.8	2.8	3.0	4.9	1.1	1.7	128.0
12	0.6	4.8	1.5	4.0	6.7	−0.4	1.9	122.0
14	1.0	7.0	3.6	3.0	6.5	1.8	1.8	96.0
16	0.8	6.1	5.2	7.8	5.8	2.5	2.7	165.0
18	0.7	6.0	0.2	3.5	6.1	−1.7	1.9	114.0
19	0.7	6.0	3.8	3.5	6.4	2.0	1.8	104.0
23	1.1	6.0	5.1	2.5	4.6	3.1	2.0	135.0
25	1.0	6.4	4.7	7.0	5.7	2.5	2.2	132.0
Total	8.7	57.6	27.9	42.3	58.8	8.3	19.6	1228.0
Average	0.87	5.76	2.79	4.23	5.88	0.83	1.96	122.8
THIRD GROUP								
26	1.6	5.3	0.4	3.5	6.2	−1.6	2.0	100.0
28	1.2	5.4	3.0	7.0	5.2	1.0	2.0	135.0
29	1.0	5.0	3.1	1.5	4.3	0.7	2.4	182.0
35	1.3	5.6	2.0	2.0	4.5	0.6	1.4	101.0
38	1.3	5.8	0.7	4.0	6.0	−1.7	2.4	145.0
39	1.0	5.0	0.3	1.8	6.0	−1.4	1.7	111.0
40	1.0	5.2	2.5	2.0	5.7	0.9	1.6	102.0
Total	8.4	37.3	12.0	21.8	37.8	−15.0	13.5	876.0
Average	1.2	5.33	1.71	3.1	5.41	−2.1	1.93	125.1

TABLE 10

ARRIVAL TIMES OF MICROSEISMIC WAVES, OCTOBER 26, 1938: MEAN VALUES OF GROUPS

Group av. no.	St. Louis University			Washington University			Difference	
	Wave		Trough-to-break interval (sec.)	Wave		Trough-to-break interval (sec.)	Time (sec.)	Phase (deg.)
	Ampl. (mm.)	Per. (sec.)		Ampl. (mm.)	Per. (sec.)			
E-W COMPONENTS								
a 1	4.3	5.7	2.79	3.9	5.5	1.65	1.14	73.5
2	5.7	5.5	3.18	5.0	5.9	2.12	1.06	67.9
3	3.8	5.2	3.07	3.0	5.0	1.88	1.19	77.8
4	5.5	5.9	3.95	5.6	5.9	2.69	1.26	77.8
5	5.3	5.5	3.9	4.0	5.8	2.62	1.28	81.5
6	2.7	5.3	2.75	3.3	5.4	1.89	0.86	56.9
7	3.4	5.7	4.41	2.5	5.6	3.12	1.28	82.6
Total	30.7	38.8	24.05	27.3	39.1	15.96	8.07	517.8
Average	4.4	5.54	3.434	3.9	5.58	2.28	1.15	73.98

Group av. no.	St. Louis University			Maryville College			Difference	
	Wave		Trough-to-break interval (sec.)	Wave		Trough-to-break interval (sec.)	Time (sec.)	Phase (deg.)
	Ampl. (mm.)	Per. (sec.)		Ampl. (mm.)	Per. (sec.)			
N-S COMPONENTS								
1	1.1	5.6	3.38	4.3	5.3	1.34	2.05	132.6
2	0.9	5.8	2.79	4.23	5.9	0.83	1.96	122.8
3	1.2	5.3	1.71	3.1	5.4	−0.21	1.93	125.1
Total	3.2	16.7	7.88	11.6	16.6	1.96	5.94	380.5
Average	1.1	5.56	2.626	3.86	5.53	6.5	1.98	126.8

For the second pair of stations of St. Louis University and Maryville College the average of the various group averages is 1.98 sec., made up of values with a

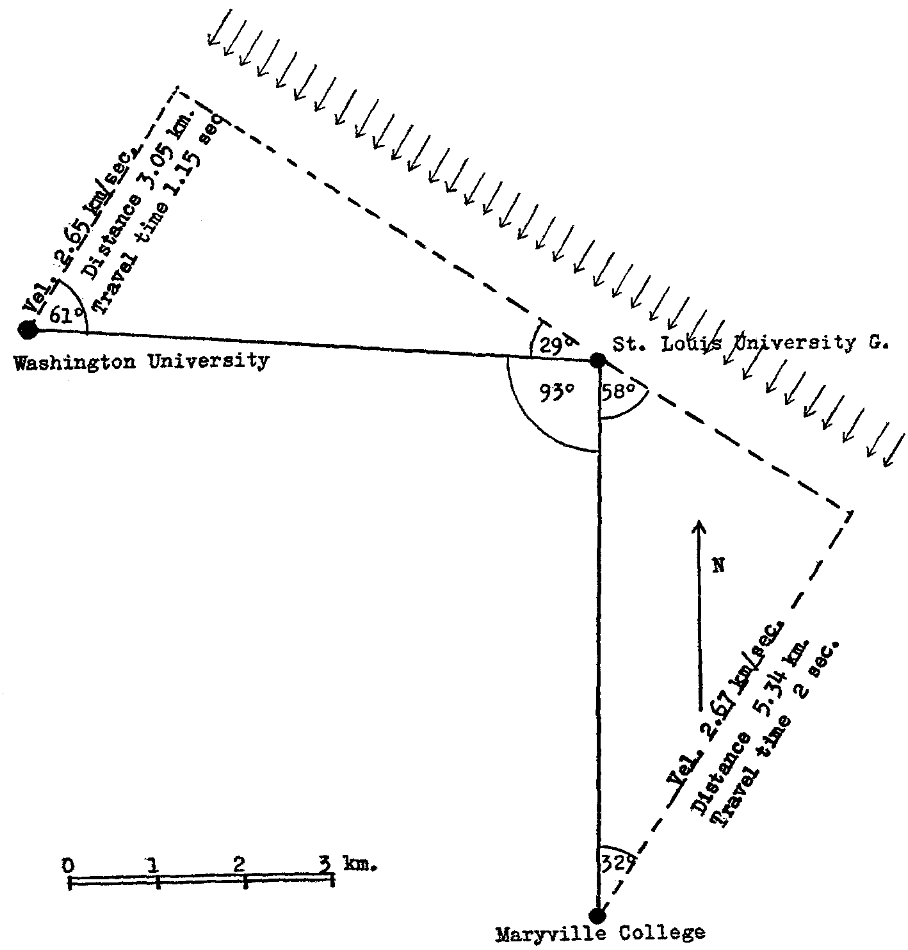


Fig. 31. Diagram showing triangles formed from the differences in the arrival times of the microseismic waves, for calculation of the velocity and the direction of microseisms at St. Louis, October 26, 1928, between 8:45 and 9:45 P.M., G.M.T. The direction was N 33° E, calculated from the mean differences in the arrival of the waves during this interval.

minimum of 1.93 and a maximum of 2.05, representing a difference of these extreme values of 0.12 sec.

From these values of t_1 and t_2 the direction and the velocity of microseisms were calculated. They are represented in figure 31. The velocity found here is between 2.65 and 2.67 km/sec., which is almost exactly the same as the one found for the storm of October 24. The direction is N 33° E.

Wave length.—In order to determine the wave length from this storm, we need to know the period and the velocity. As shown in table 10, the average period of all the average groups of the first pair of stations is 5.54, and for the second pair, 5.56. Taking the mean of these two average periods, we get a

TABLE 11

MICROSEISMIC STORM, AUGUST 15–16, 1938

(Amplitudes and periods as read from the four records every hour, near the hour, during the strong part of the storm)

Time	E-W component				N-S component			
St. Louis local time	St. Louis University		Washington University		St. Louis University		Maryville College	
	Ampl. (mm.)	Per. (sec.)	Ampl. (mm.)	Per. (sec.)	Ampl. (mm.)	Per. (sec.)	Ampl. (mm.)	Per. (sec.)
P.M.								
4	0.8	4.3	0.7	4.3	0.6	4.0	0.8	5.0
5	0.7	4.2	0.7	4.1	0.7	4.1	0.7	4.0
6	0.7	3.9	0.7	4.0	0.6	4.2	0.7	4.2
7	0.8	4.0	0.7	4.4	0.7	4.2	0.7	4.2
8	0.9	4.0	0.5	4.2	10.8	4.3	1.0	4.2
9	1.1	4.0	1.1	4.5	1.0	4.4	1.2	4.6
10			1.1	4.6	0.9	4.2	0.9	4.4
11	Readings interfered with by an earthquake.							
12 mid	Readings interfered with by an earthquake.							
Aug. 16								
A.M.								
1	2.0	4.7	1.2	4.6	1.6	4.9	1.0	4.6
2	1.8	4.5	1.8	4.4	1.5	5.0	2.0	4.5
3	1.9	4.6	1.8	5.0	2.1	5.1	1.5	4.4
4	1.9	4.4	2.1	5.0	2.2	5.0	2.1	5.0
5	2.2	5.2	2.2	5.2	1.9	5.1	2.6	4.2
6	2.1	4.5	1.7	4.8	2.1	5.1	1.6	4.8
7	2.1	5.0	2.0	5.1	2.0	5.0	2.4	5.0
8	2.0	5.2	2.0	5.2	2.1	5.2	1.8	4.8
9	1.8	5.1	1.3	5.0	1.6	5.3	2.2	4.6
10	1.8	5.2	1.8	5.2	1.7	5.4	1.6	4.6
11	1.6	5.1	2.0	5.0	2.0	5.3	9.8	5.0

period of 5.55 sec. If we take an average velocity of microseismic waves of 2.66 km/sec., we get a wave length of $\lambda = vt = 14.76$ km.

All other measurements taken of the arrival times of microseismic waves give much the same results, and each of them offers a splendid check on the calculations and methods mentioned here with regard to the velocity, direction, and wave length of microseismic waves.

One storm is of particular interest because it is perhaps the only one of not-able amplitudes (about 1 mm.) that belongs to the summer microseisms. Table 11 shows the amplitudes and periods at the height of this storm, and table 12 the arrival-time differences of waves at each pair of stations. The value of the

TABLE 12

ARRIVAL-TIME DIFFERENCES OF MICROSEISMIC WAVES AT THE TWO PAIRS OF STATIONS, AUGUST 16, 1938, BETWEEN 4:00 AND 5:00 A.M.

E-W		Difference (sec.)	N-S		Difference (sec.)
St. Louis U. trough-to-break interval	Washington U. trough-to-break interval		St. Louis U. trough-to-break interval	Maryville C. trough-to-break interval	
5.4	4.25	1.15	3.7	1.71	1.99
2.95	2.5	0.45	5.05	3.45	1.55
2.45	1.9	0.55	3.7	1.2	2.5
6.0	5.35	0.65	2.95	0.73	2.12
5.1	3.9	1.2	6.8	4.45	2.35
3.1	2.55	0.55	4.05	2.0	2.05
3.3	2.6	0.7	4.2	2.4	1.8
4.2	2.8	1.2	2.1	0.25	1.85
2.0	1.0	1.0	5.4	3.67	1.73
3.8	2.8	1.0	4.05	2.0	2.05
1.85	1.35	0.5	4.16	2.16	2.0
1.0	0.55	0.45	5.15	3.2	1.95
2.1	1.5	0.6	5.2	2.9	2.3
2.3	1.4	0.9	5.65	3.3	2.35
3.3	2.5	0.8	5.6	3.5	2.1
3.5	2.7	0.8	4.9	3.0	1.9
4.5	3.4	1.1	5.6	3.15	2.45
3.9	3.2	0.7	5.5	3.3	2.2
5.1	3.7	1.4	6.1	3.7	2.4
3.8	3.1	0.7	4.1	2.2	1.9
5.5	5.0	0.5	5.7	3.3	2.4
1.7	1.2	0.5	2.6	0.3	2.3
0.6	0.0	0.6	5.1	2.8	2.3
3.1	2.3	0.8	2.8	0.8	2.0
3.2	2.6	0.6	3.7	1.6	2.1
3.4	2.7	0.7	4.7	2.75	1.95
Total 87.15	66.85	20.47	118.56	63.82	54.59
Aver. 3.35	2.57	0.79	4.55	22.45	2.1

velocity of microseismic waves obtained from these figures is about 0.05 above the normal value of other storms. The direction of the storm was N 23° E.

From the different storms studied, it was possible to construct by interpolation a chart indicating the direction of microseisms for the most common quarter, that is, between N and E, with the corresponding time differences between the stations of St. Louis and Maryville. (See fig. 32.)

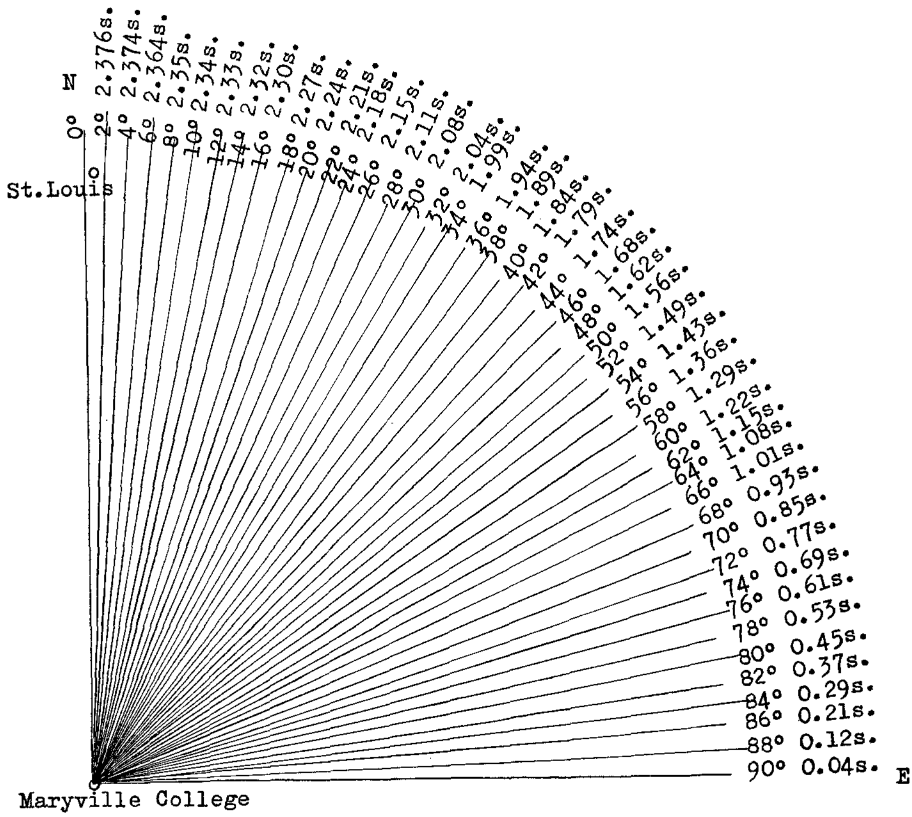


Fig. 32. Chart indicating the direction of microseisms for the most common quarter, with the corresponding time differences between the stations at St. Louis and Maryville.

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END OF PART ONE

Part Two will appear in the next number of the *Bulletin*