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Seismic Noise Survey in Long Valley, California

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In June 1973, seismic noise measurements were made in Long Valley, California, as part of the U.S. Geological Survey's geothermal investigations. Spatial variation of the average noise power shows high levels of noise extending over most of the eastern half of the Long Valley caldera. Since the noise high is almost similar in extent to the soft sedimentary Owens River basin, it is possible that ground amplification of seismic waves is at least partially responsible for the noise anomaly. Two lines of evidence indicate that geothermal noise may be present in Long Valley. (1) Relative amplification of teleseismic waves over soft ground, with respect to a reference station on hard rock, is about 12 dB. The noise anomaly, however, is at least 12 dB higher than this value. It is therefore difficult to explain the anomaly by postulating ground amplification of regional noise, thus indicating that a noise source may be present in the area of the anomaly. At wave frequencies below 2 Hz, river and cattle noise do not contribute much to the anomaly. (2) Group velocities of seismic noise, measured by using arrays, are in general quite low except at a few stations along the southern edge of the noise anomaly. The wave azimuths in the low-velocity areas show random propagation, whereas azimuths associated with the high-velocity waves point to the area where surface geothermal phenomena are found. The high-velocity waves also have frequencies below 2 Hz. If a noise source is present under the southern edge of the sedimentary basin, it could excite the basin much more than it does the hard ground directly above it and thus produce the observed noise anomaly.

INTRODUCTION

Even though there is considerable interest in using seismic noise in the frequency band of 1–10 Hz as a prospecting tool for geothermal energy, clear correlation between high noise levels and active hydrothermal reservoirs has been demonstrated only in very few regions [*Whiteford,* 1970; *Iyer and Hitchcock,* 1974]. The main problem is that cultural noise and noise generated by rivers and wind are in the same frequency band as geothermally generated seismic noise and often cause confusion in identifying the latter [*Douze and Sorrells,* 1972; *Iyer,* 1974]. As we shall show, ground conditions can cause amplification of background seismic noise; when this occurs in a geothermal area, it is difficult to interpret a seismic noise anomaly. Many case histories, such as the one on Long Valley to be discussed here, may eventually provide the material to evaluate the usefulness of seismic noise as a geothermal prospecting tool.

FIELD EXPERIMENT

The seismic noise survey in Long Valley during June 1973 follows the general procedure developed by the U.S. Geological Survey for noise studies in Imperial Valley, California, and Yellowstone National Park, Wyoming [*Iyer,* 1974; *Iyer and Hitchcock,* 1974]. EV-17 seismometers with slow-speed tape-recording systems (described by *Eaton et al.* [1970]) were used in the experiment. Profiles of 8 stations, with average spacing of about 2 km, were operated for 48 hours and then moved to a new location. One of two stations in a quiet area over hard ground was operated continuously during the entire period of the experiment. Nine stations had one vertical and two horizontal seismometers, 16 stations had three instruments arranged as an L array with 106-m instrument spacing, and the rest were single-component stations with vertical seismometers (Figure 1). Eight of the stations were reoccupied for 3 nights during November 1974. Noise measurements were also made for 1 night in Owens Valley near the town of Bishop, about 50 km south of Long Valley. The locations of stations and durations of their operations are given in Table 1.

DATA ANALYSIS

Analog tapes for the whole recording period were played back, and the records were carefully examined for instrumental malfunctions, cultural noise, transients, and earthquakes. In general, it is found that noise levels are much higher and more transients are present during the day than at night. Hence an hour-long data sample was selected from the quietest section of the night record for each profile and digitized at a rate of 50 samples per second. Samples at a permanent station were taken at approximately the same time as at the profile stations.

Two types of computations were performed on the digitized data. Spectral analysis of a typical noise sample of 40.96-s duration was done by using techniques developed for our Imperial Valley noise survey [*Iyer,* 1974]. Examination of several spectra shows that the predominant seismic noise energy in Long Valley is in the frequency band of 0.5–4 Hz. To study the spatial variation of noise energy in different frequency bands, the hour-long data sample is digitally filtered in frequency bands of 0–1, 1–2, 2–4, and 4–8 Hz, and average rms values are computed for successive 81.92-s data blocks. (The summation over the 0- to 1-Hz band representing low-frequency energy is uncorrected for seismometer response. Since the seismometer response drops off sharply below 1 Hz, there is very little contribution from seismic frequencies below about 0.25 Hz in this band.) The total unfiltered seismic energy is also calculated for each block. Out of the 43 values thus computed for each hour-long sample the quietest 30 were averaged to give a representative noise level in millimicrons per second of ground velocity.

Our noise survey at Long Valley lasted for 4 weeks. As mentioned earlier, the variation of noise level during this period was monitored by one of two reference stations, P2 and P3 (Figure 1), where noise levels are similar. The noise level in different frequency bands at these stations (Figure 2) varied somewhat during the period of the experiment. Because the profiles of stations in different areas were operated on different days, the observed noise levels have to be corrected for this regional variation. This correction is accomplished by computing relative noise levels (ratio of noise level at each station

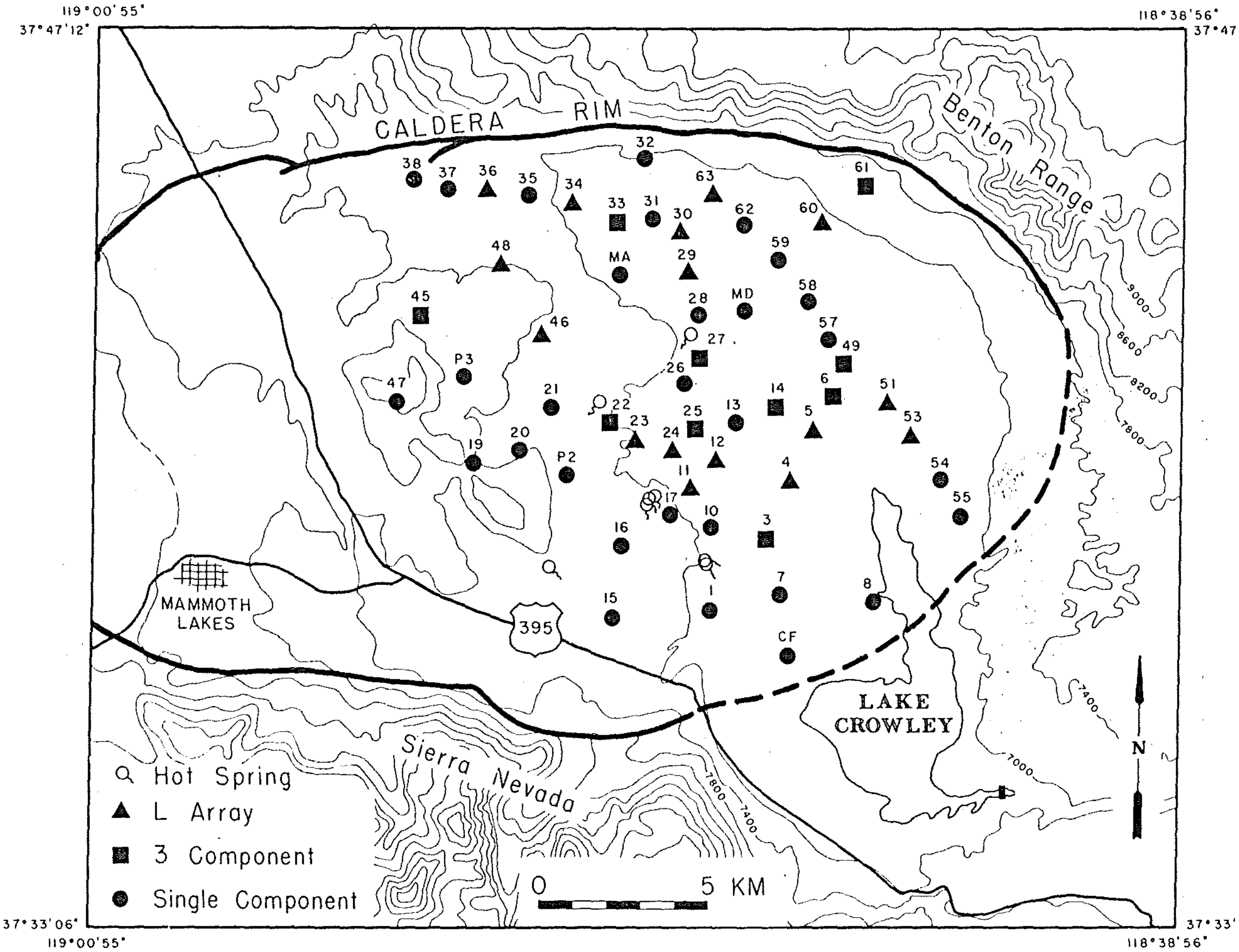

Fig. 1. Location of seismic stations in Long Valley. Numbers are station identifications; caldera boundary from geological evidence is shown by solid line where it is definite and by dashed line where it is indefinite.

to noise level at the reference station) and using them instead of actual noise levels in the plots. Samples at the reference stations were taken at the same time as the samples at the other stations in order to evaluate relative noise levels. The noise levels at the reference stations for the 11 nights shown in Figure 2 were sufficient to calculate relative noise levels at all the stations. In doing this correction it is assumed that the temporal variation of noise at the reference stations is representative of variation in the whole region and is not a local phenomenon associated with those stations. In any case, since the maximum spatial variation of noise levels is much higher than the maximum variation at the reference station during the experiment, the correction for temporal variation does not drastically change the shape of the noise anomalies discussed below.

THE NOISE ANOMALY IN LONG VALLEY

Figures 3*a*–3*e* show the spatial variation of noise levels for four frequency bands and for unfiltered data. The units are in decibels with respect to P2 or P3. The most obvious feature of the noise level distribution is the energy high extending over most of the eastern half of the caldera. The anomaly has an amplitude of 12–18 dB in the 0- to 1-Hz band and 12–30 dB in the other frequency bands and unfiltered data. The peak of the anomaly is about 10 km long and 5 km wide. The gradients are very sharp east and west of this peak. However, there are two disturbing aspects to this anomaly. First, it is outside the area where the majority of hot springs in Long Valley are present (Figure 1), and second, it roughly coincides in extent to a soft sedimentary basin traversed by the Owens River and many small streams. The existence of about 500 m of sedimentary material of lower density than the underlying rock in this area is inferred from interpretation of a seismic refraction survey in Long Valley [*Hill*, 1976]. Sedimentary basins amplify ground motion associated with seismic waves. The amplification is usually caused by soft surficial layers of thickness comparable to the seismic wavelength. We shall show below that the group velocity of seismic noise waves in Long Valley is only of the order of 150 m/s at 2-Hz frequency. It was not possible to estimate phase velocity and hence wavelength. We believe, however, that the soft water-saturated river valley deposits in the region of the Owens River, which are probably only a few tens of meters thick and overlie the thicker sediments found by the refraction survey, are responsible for the noise anomaly. The alluvium can be excited by one or more of the following noise sources: (1) the regional background noise, which is about 40 mμ/s at P2, one of the quietest stations over hard ground; (2) river noise; (3) cattle (several hundred cattle were present on the pasture lands along the river during the experiment); and (4) the geothermal system.

GROUND AMPLIFICATION

Whatever may be the source of noise in Long Valley, the amplification of seismic waves by the Owens River basin is an

TABLE 1. Location of Noise Survey Stations and Their Time of Operation

Station	Latitude	Longitude	Day On	Time, UT	Day Off	Time, UT
P2	37°40′25″	118°51′25″	June 7, 1973	09h 39m	June 23, 1973	19h 23m
P2	37°40′25″	118°51′25″	Nov. 5, 1974	18h 55m	Nov. 9, 1974	19h 50m
P3	37°41′75″	118°53′36″	June 19, 1973	21h 52m	July 2, 1973	13h 45m
1	37°38′12″	118°48′32″	June 7, 1973	07h 52m	June 12, 1973	19h 30m
3	37°39′27″	118°47′25″	June 7, 1973	00h 49m	June 10, 1973	00h 37m
4	37°40′15″	118°46′75″	June 7, 1973	02h 40m	June 10, 1973	15h 50m
5	37°40′93″	118°46′28″	June 7, 1973	04h 20m	June 9, 1973	20h 15m
6	37°41′50″	118°45′89″	June 7, 1973	05h 52m	June 15, 1973	17h 45m
7	37°38′38″	118°46′90″	June 7, 1973	08h 20m	June 9, 1973	23h 07m
8	37°38′27″	118°45′05″	June 7, 1973	08h 44m	June 9, 1973	22h 26m
10	37°39′41″	118°48′35″	June 11, 1973	01h 30m	June 12, 1973	23h 18m
11	37°40′01″	118°48′78″	June 11, 1973	03h 08m	June 16, 1973	19h 20m
11	37°40′01″	118°48′78″	Nov. 7, 1974	00h 05m	Nov. 9, 1974	14h 52m
12	37°40′46″	118°48′25″	June 11, 1973	04h 08m	June 15, 1973	20h 15m
13	37°41′08″	118°47′87″	June 11, 1973	04h 45m	June 15, 1973	19h 32m
13	37°41′08″	118°47′87″	Nov. 7, 1974	00h 30m	Nov. 9, 1974	16h 58m
14	37°41′32″	118°47′02″	June 11, 1973	05h 10m	June 15, 1973	18h 55m
15	37°37′98″	118°50′26″	June 13, 1973	21h 42m	June 16, 1973	17h 26m
15	37°37′98″	118°50′26″	July 5, 1973	02h 35m	July 5, 1973	18h 45m
16	37°39′12″	118°50′14″	June 13, 1973	22h 39m	June 16, 1973	18h 05m
16	37°39′12″	118°50′14″	July 5, 1973	01h 34m	July 5, 1973	18h 10m
17	37°39′63″	118°49′18″	June 13, 1973	23h 34m	June 16, 1973	18h 45m
17	37°39′63″	118°49′18″	July 5, 1973	00h 34m	July 5, 1973	17h 40m
19	37°40′40″	118°53′17″	June 16, 1973	00h 20m	June 18, 1973	19h 31m
20	37°40′61″	118°52′20″	June 16, 1973	23h 06m	June 18, 1973	19h 50m
21	37°40′30″	118°51′57″	June 16, 1973	03h 05m	June 18, 1973	20h 05m
22	37°41′05″	118°50′39″	June 16, 1973	02h 01m	June 19, 1973	22h 46m
23	37°40′75″	118°49′88″	June 16, 1973	21h 55m	June 19, 1973	23h 02m
24	37°40′62″	118°49′12″	June 16, 1973	00h 41m	June 19, 1973	23h 52m
25	37°40′97″	118°48′67″	June 15, 1973	22h 35m	June 21, 1973	16h 47m
26	37°41′66″	118°48′88″	June 19, 1973	03h 56m	June 22, 1973	19h 20m
27	37°42′06″	118°48′60″	June 20, 1973	05h 30m	June 21, 1973	18h 45m
27	37°42′06″	118°48′60″	Nov. 6, 1974	20h 55m	Nov. 9, 1974	15h 22m
28	37°42′75″	118°48′63″	June 19, 1973	02h 35m	June 21, 1973	18h 15m
29	37°43′35″	118°48′85″	June 20, 1973	04h 45m	June 21, 1973	19h 14m
29	37°43′35″	118°48′85″	Nov. 6, 1974	23h 30m	Nov. 9, 1974	16h 20m
30	37°44′01″	118°49′03″	June 20, 1973	04h 05m	June 21, 1973	19h 54m
31	37°44′27″	118°49′57″	June 18, 1973	23h 43m	June 21, 1973	17h 47m
32	37°45′25″	118°49′67″	June 19, 1973	01h 37m	June 21, 1973	17h 15m
33	37°44′20″	118°50′34″	June 21, 1973	22h 35m	June 23, 1973	20h 12m
34	37°44′46″	118°51′26″	June 22, 1973	23h 21m	June 24, 1973	18h 32m
35	37°44′62″	118°52′09″	June 22, 1973	01h 52m	June 23, 1973	20h 34m
36	37°44′66″	118°52′97″	June 23, 1973	01h 11m	June 24, 1973	19h 38m
37	37°44′72″	118°53′75″	June 23, 1973	01h 58m	June 24, 1973	20h 28m
38	37°44′87″	118°54′46″	June 22, 1973	00h 20m	June 23, 1973	21h 10m
45	37°42′71″	118°54′30″	June 25, 1973	00h 42m	June 26, 1973	18h 40m
46	37°42′38″	118°51′80″	June 25, 1973	02h 10m	June 26, 1973	19h 22m
47	37°41′36″	118°54′73″	June 25, 1973	04h 53m	June 26, 1973	17h 18m
48	37°43′48″	118°52′66″	June 25, 1973	03h 36m	June 26, 1973	20h 25m
49	37°42′00″	118°45′67″	June 26, 1973	00h 28m	July 1, 1973	23h 07m
51	37°41′38″	118°44′80″	June 27, 1973	00h 44m	June 29, 1973	18h 30m
53	37°40′87″	118°44′29″	June 27, 1973	02h 20m	June 29, 1973	17h 57m
54	37°40′21″	118°43′66″	June 27, 1973	03h 01m	June 29, 1973	20h 22m
55	37°39′65″	118°43′26″	June 27, 1973	03h 57m	June 29, 1973	19h 55m
57	37°42′38″	118°46′01″	June 29, 1973	00h 10m	July 1, 1973	22h 40m
58	37°43′00″	118°46′41″	June 28, 1973	21h 17m	July 1, 1973	22h 04m
59	37°43′65″	118°47′04″	June 30, 1973	01h 52m	July 1, 1973	19h 16m
59	37°43′65″	118°47′04″	Nov. 7, 1974	01h 45m	Nov. 9, 1974	17h 45m
60	37°44′20″	118°46′23″	June 30, 1973	03h 14m	July 1, 1973	20h 50m
61	37°44′80″	118°45′33″	June 28, 1973	22h 40m	July 1, 1973	19h 55m
61	37°44′80″	118°45′33″	Nov. 7, 1974	02h 28m	Nov. 9, 1974	18h 40m
62	37°44′20″	118°47′77″	June 30, 1973	00h 35m	July 1, 1973	18h 44m
63	37°44′63″	118°48′41″	June 29, 1973	23h 25m	July 1, 1973	17h 42m
64	37°19′33″	118°17′64″	July 3, 1973	03h 19m	July 3, 1973	19h 00m
65	37°19′46″	118°18′20″	July 3, 1973	02h 48m	July 3, 1973	19h 00m
66	37°19′48″	118°19′00″	July 3, 1973	02h 05m	July 3, 1973	19h 00m
67	37°19′56″	118°19′57″	July 3, 1973	06h 25m	July 3, 1973	19h 00m
68	37°19′55″	118°20′05″	July 3, 1973	05h 52m	July 3, 1973	19h 00m
69	37°19′58″	118°20′58″	July 3, 1973	05h 20m	July 3, 1973	19h 00m
70	37°19′56″	118°21′10″	July 3, 1973	04h 52m	July 3, 1973	19h 00m
71	37°19′53″	118°21′67″	July 3, 1973	03h 55m	July 3, 1973	19h 00m
72	37°18′89″	118°20′62″	July 3, 1973	01h 23m	July 3, 1973	19h 00m
73	37°18′39″	118°20′46″	July 3, 1973	00h 44m	July 3, 1973	19h 00m
MA	37°43′89″	118°50′25″	July 1, 1973	02h 10m	July 4, 1973	03h 05m
MD	37°42′85″	118°47′71″	July 6, 1973	04h 10m	July 6, 1973	14h 52m
MD	37°42′85″	118°47′71″	Nov. 6, 1974	22h 30m	Nov. 9, 1974	15h 50m
CF	37°37′43″	118°46′73″	June 29, 1973	01h 40m	July 2, 1973	00h 00m

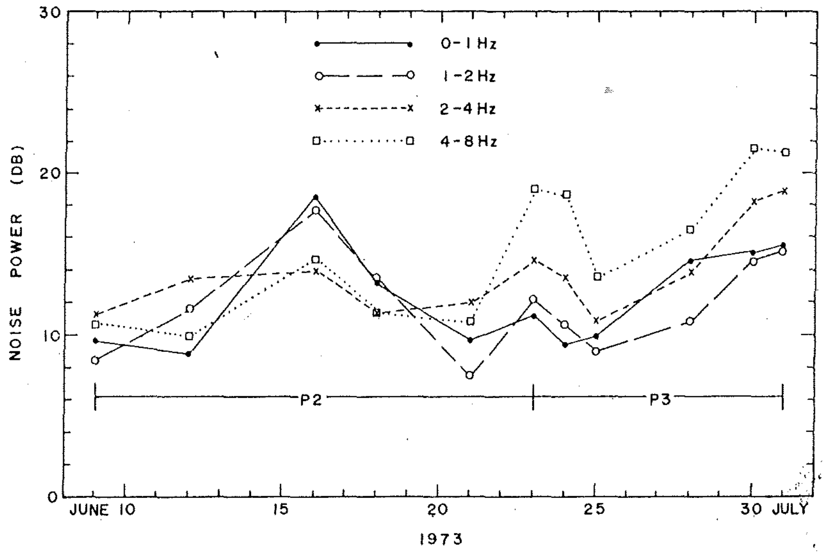

Fig. 2. Variation of noise levels in four frequency bands at reference stations P2 and P3 during the period of the experiment.

important parameter in understanding the noise anomaly. It is well known that seismic noise amplitudes are usually higher over alluvium and soft sedimentary basins. It is very difficult to make theoretical computations of noise amplification in such structures, even if the compressional and shear wave velocities are known, because of the complexity of wave types in seismic noise. Considerable work, however, has been done on theoretical and experimental computations of ground amplification of seismic waves from earthquakes with a view to understanding and overcoming earthquake damage. *Borcherdt* [1970] studied ground amplification in the San Francisco Bay area by comparing spectra of seismic waves from nuclear shots in Nevada, recorded by bedrock reference stations and at various locations over younger and older bay muds. He found (see Table 5 of his paper) that the ground amplification (ratio of seismic spectra at bay mud stations to the spectrum at the reference station on hard rock) of the horizontal and vertical components of ground motion was characterized by sharp peaks whose frequencies could be correlated with thickness of the bay muds. The ground motion was also much higher over

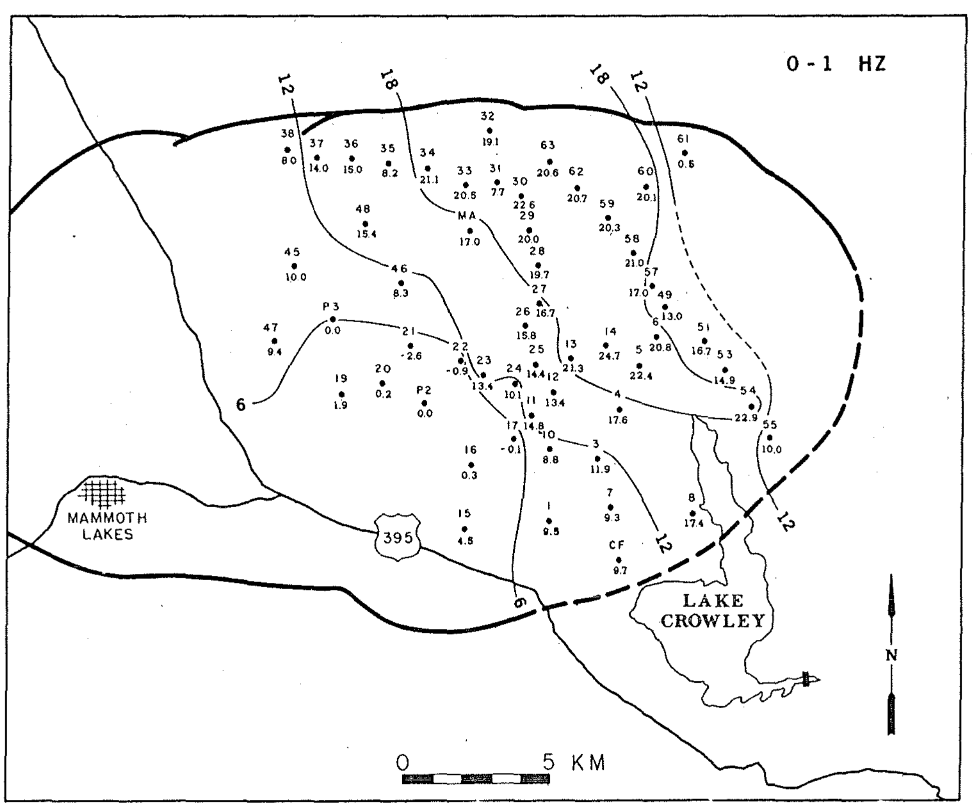

Fig. 3*a*. Spatial variation of noise level in the 0- to 1-Hz band. Dots are stations, station identification is shown by numbers above dots, relative noise levels, in decibels with respect to P2 or P3, are shown below dots, and the contour interval is 6 dB.

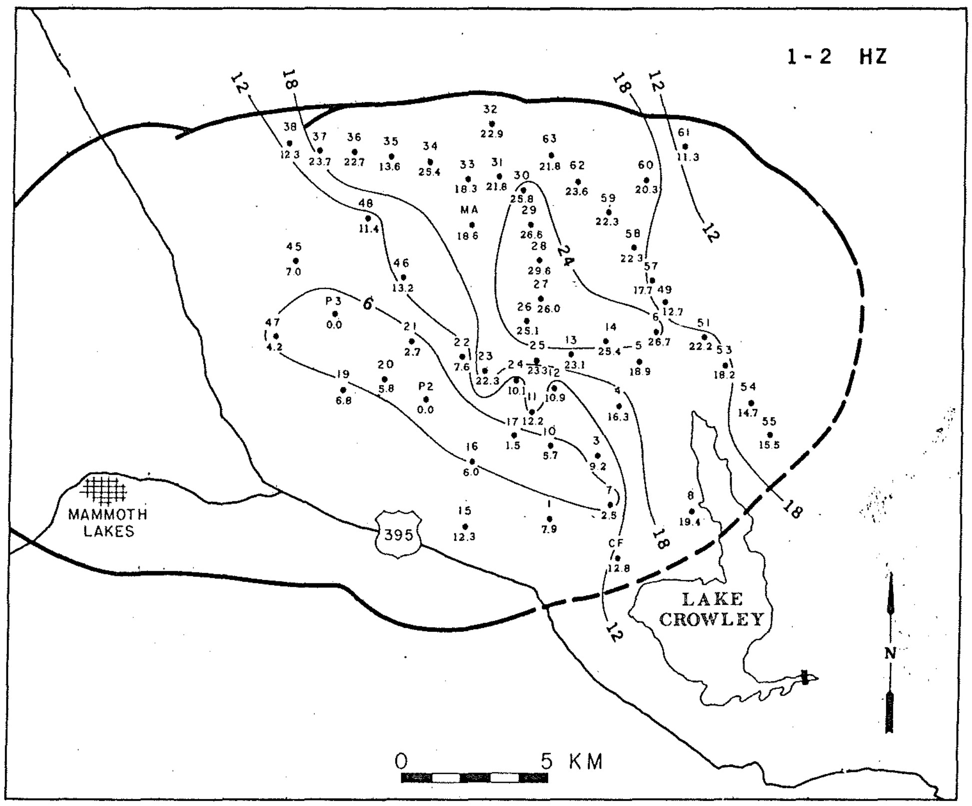

Fig. 3*b*. Spatial variation of noise level in the 1- to 2-Hz band. Dots are stations, station identification is shown by numbers above dots, relative noise levels, in decibels with respect to P2 or P3, are shown below dots, and the contour interval is 6 dB.

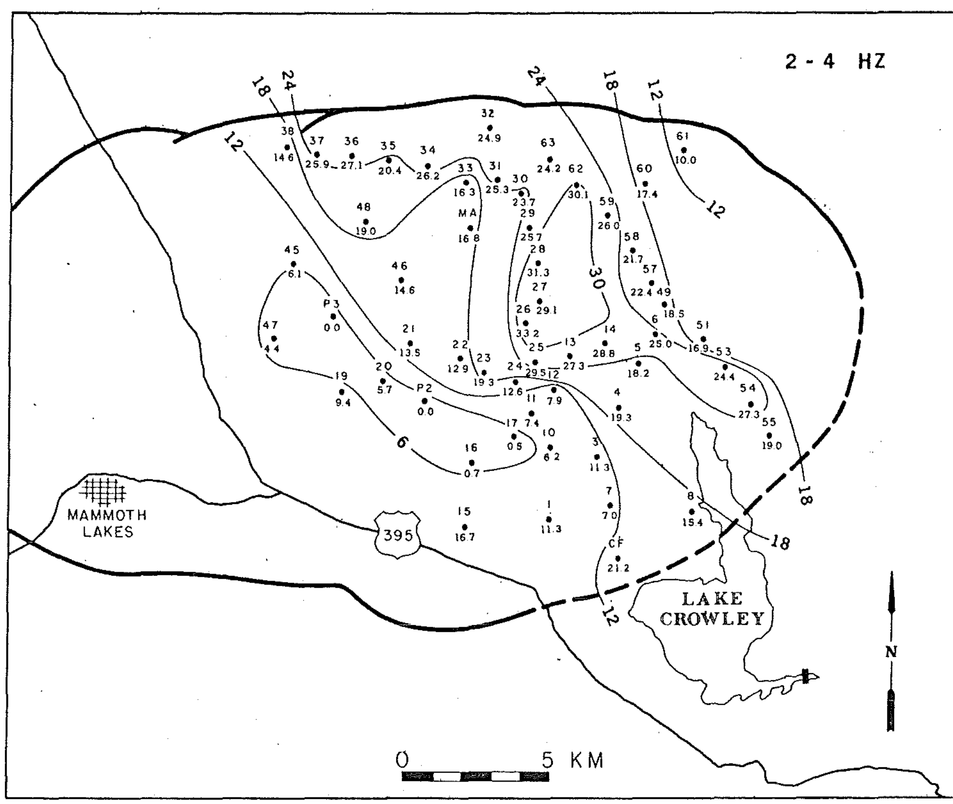

Fig. 3*c*. Spatial variation of noise level in the 2- to 4-Hz band. Dots are stations, station identification is shown by numbers above dots, relative noise levels, in decibels with respect to P2 or P3, are shown below dots, and the contour interval is 6 dB.

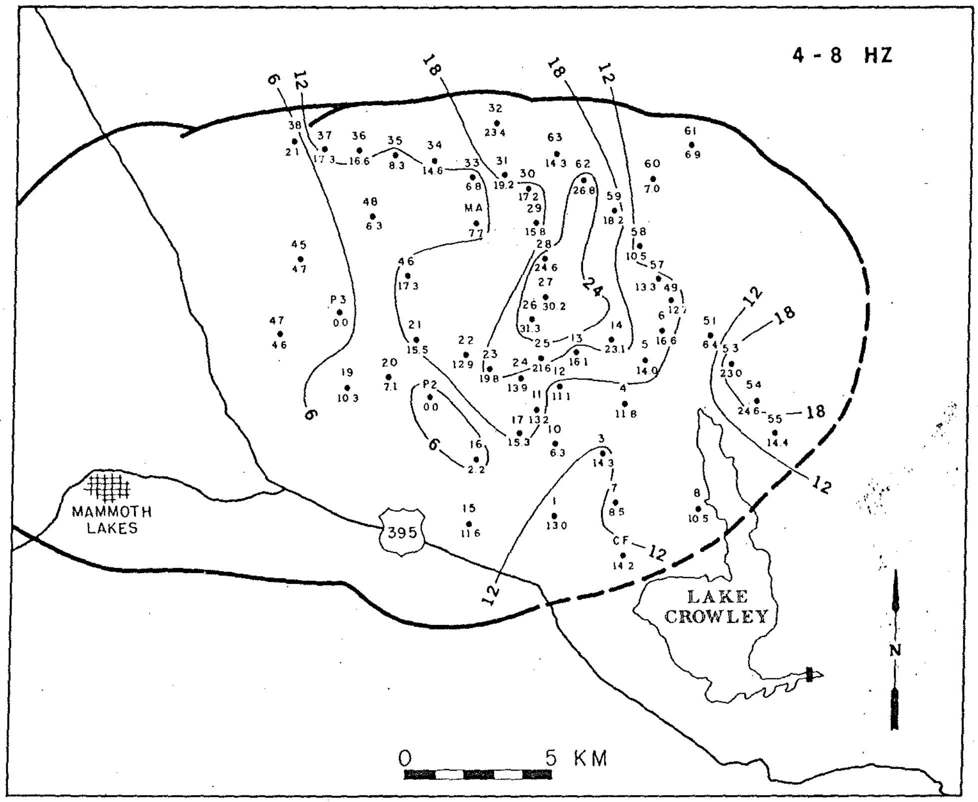

Fig. 3*d*. Spatial variation of noise level in the 4- to 8-Hz band. Dots are stations, station identification is shown by numbers above dots, relative noise levels, in decibels with respect to P2 or P3, are shown below dots, and the contour interval is 6 dB.

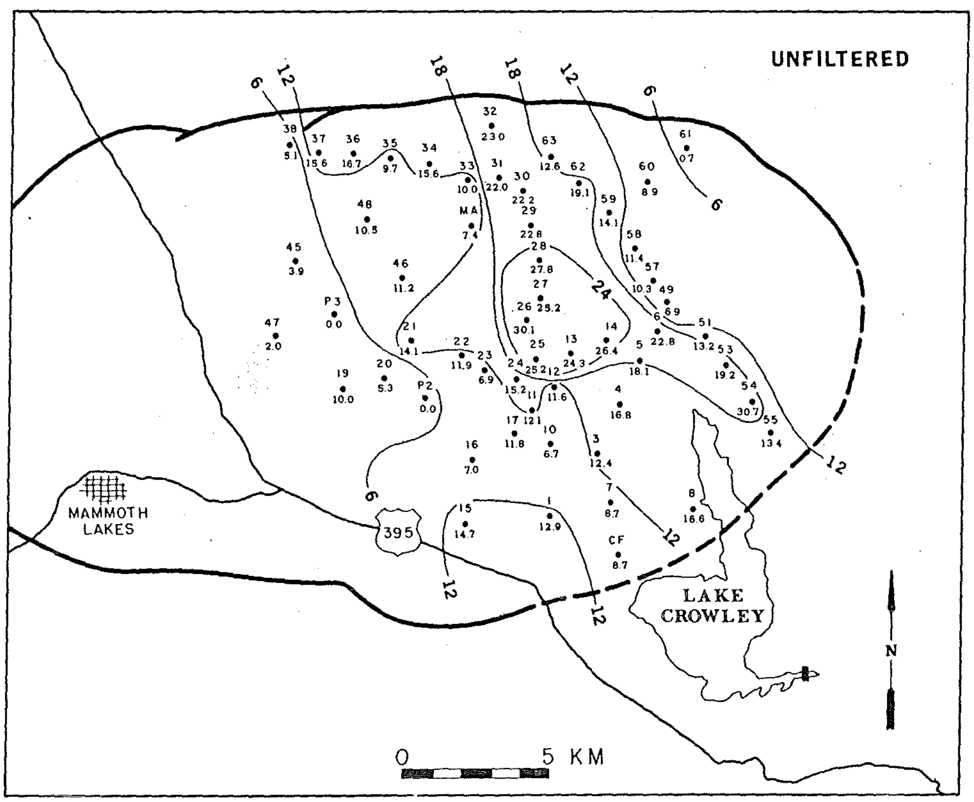

Fig. 3*e*. Spatial variation of noise level using unfiltered data. Dots are stations, station identification is shown by numbers above dots, relative noise levels, in decibels with respect to P2 or P3, are shown below dots, and the contour interval is 6 dB.

TABLE 2. Seismic Events Used in Ground Motion Study and Stations Recording Each Event

Date	Origin	Origin Time, UT	Latitude	Longitude	Magnitude	Depth, km	Recording Stations
June 9, 1973	Solomon Islands	08h 21m 27.3s	10.3°S	161.4°E	6.3	70	P2, 1, 3, 4, 5, 6, 7, 8
June 12, 1973	Southern Nevada	08h 15m 49.9s	37.2°N	116.3°W	4.8	5	P2, 10, 11, 12, 13, 14
June 16, 1973	Off Coast of Oregon	14h 43m 47.5s	45.0°N	125.8°W	5.6	33	P2, 15, 16, 17, 21, 22, 24
June 17, 1973	Hokkaido, Japan	03h 55m 02.9s	43.2°N	145.8°E	6.5	48	P2, 19, 20, 13
June 21, 1973	Unidentified	...	...	...	...	...	P2, 25, 26, 27, 28, 29, 30, 31, 32
June 28, 1973	Southern Nevada (NTS)	19h 15m 12.4s	37.1°N	116.1°W	4.9	0	P3, 51, 53, 54, 55
July 1, 1973	Off Coast of S. Alaska	13h 33m 34.6s	57.8°N	137.3°W	6.1	33	P3, 49, 57, 58, 59, 60, 62, 63, MA, CF
July 3, 1973	Southeastern Alaska	16h 59m 35.1s	58.0°N	138.0°W	6.0	33	64, 65, 66, 67, 68, 70, 71, 72, 73

bay muds than over hard rock. The average vertical ground velocity was about 4 times higher over younger bay muds from 7 to 23 m in thickness and about 2 times higher over older bay muds from 30 to 600 m in thickness. The maximum ground amplification occurred in the 1- to 2-Hz frequency band.

Ground amplification calculations in Long Valley using earthquake waves. Several teleseisms and blasts from Nevada Test Site (NTS) were recorded during our noise survey in Long Valley. Some of the events were sufficiently well recorded at the reference stations and the mobile stations so as to enable ground amplification calculations. Details of the seismic events used in the study and a list of stations recording them are given in Table 2. Spectra of the first 40 s of the seismic signal at each of the mobile stations are compared with the spectrum at the appropriate reference station. The ratio of the spectrum at the mobile station to the spectrum at the reference station gives the ground amplification spectrum. Both noise and event signals are amplified, but when the seismic wave amplitude from the event is much larger than the noise amplitude, the ground amplification measurement can be taken to be that associated with the seismic waves from the event. Noise spectra are computed for a sample just prior to the event, and only ground amplification values at frequencies where the event spectrum is at least 6 dB or more than noise spectrum are used. With this criterion the ground amplification values above 2 Hz are not meaningful except for one profile. In addition to a noise sample just prior to the event, the spectral ratio of a quiet noise sample at the mobile station to the reference stations is computed for comparison with the ground amplification spectrum.

Figure 4 shows typical analog seismograms along a profile

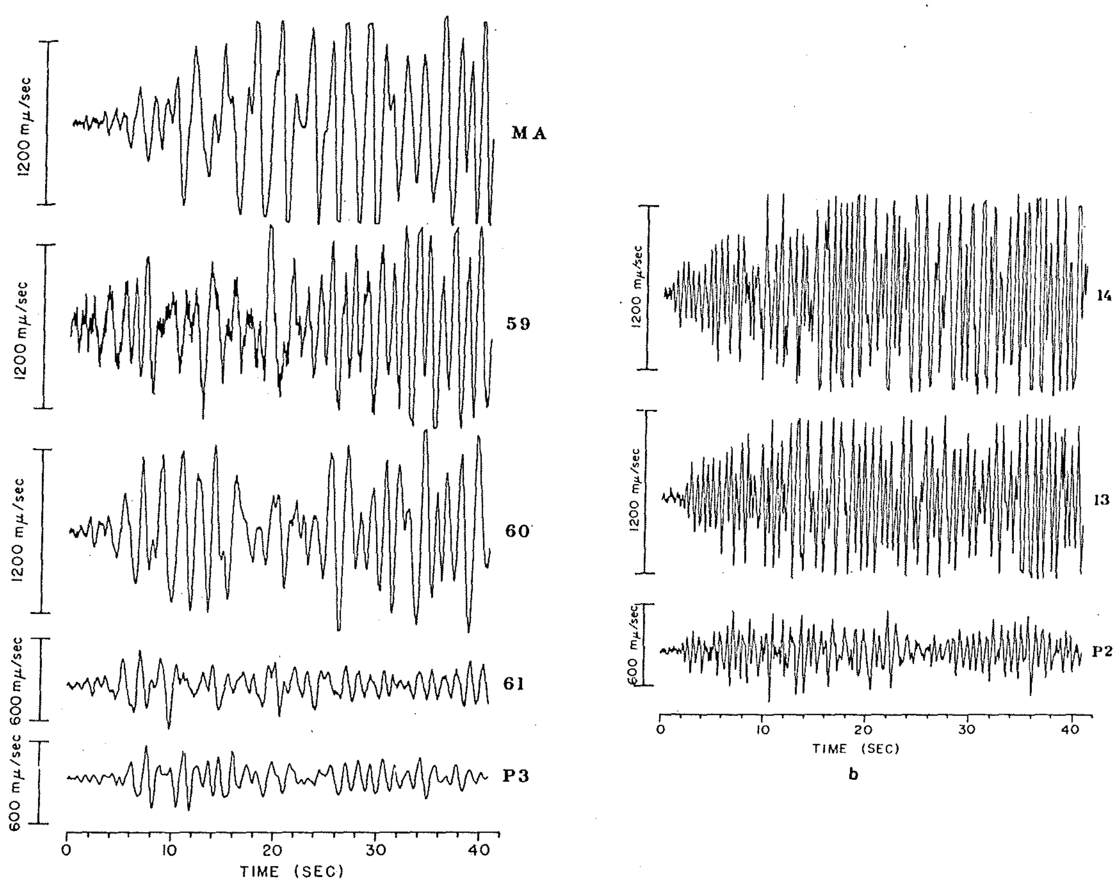

Fig. 4. Analog seismograms to show ground amplification at (left) stations P3 (reference), 59, MA, 60, and 61 for Alaskan event, and (right) P2 (reference), 13, and 14 for NTS event.

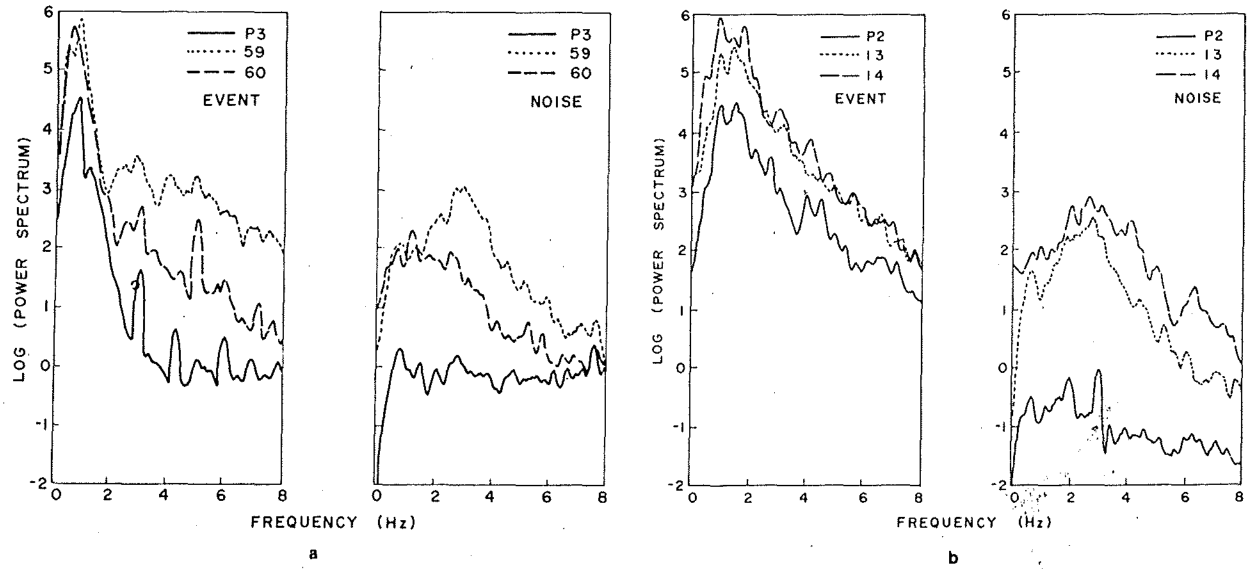

Fig. 5. Comparison of event spectra and noise spectra at (left) stations 59, 60, and P3 and (right) stations 13, 14 and P2.

from the northeast rim of the caldera toward the center of the sedimentary basin to illustrate the ground amplification problem in Long Valley. Note that the seismograms at P3 on hard ground and 61, also on hard ground at the caldera rim, have more or less the same amplitude. The signals increase in amplitude by a factor of 4 between 61 and MA as the thickness of the sediment increases (Figure 4*a*). Similarly, a comparison of seismic signals from a regional event from Nevada (NTS shot) shows large ground amplification at stations 13 and 14 over sediments near the center of the eastern half of the caldera (Figure 4*b*). The spectra shown in Figure 5 illustrate these results quantitatively. The earthquake signals are amplified by

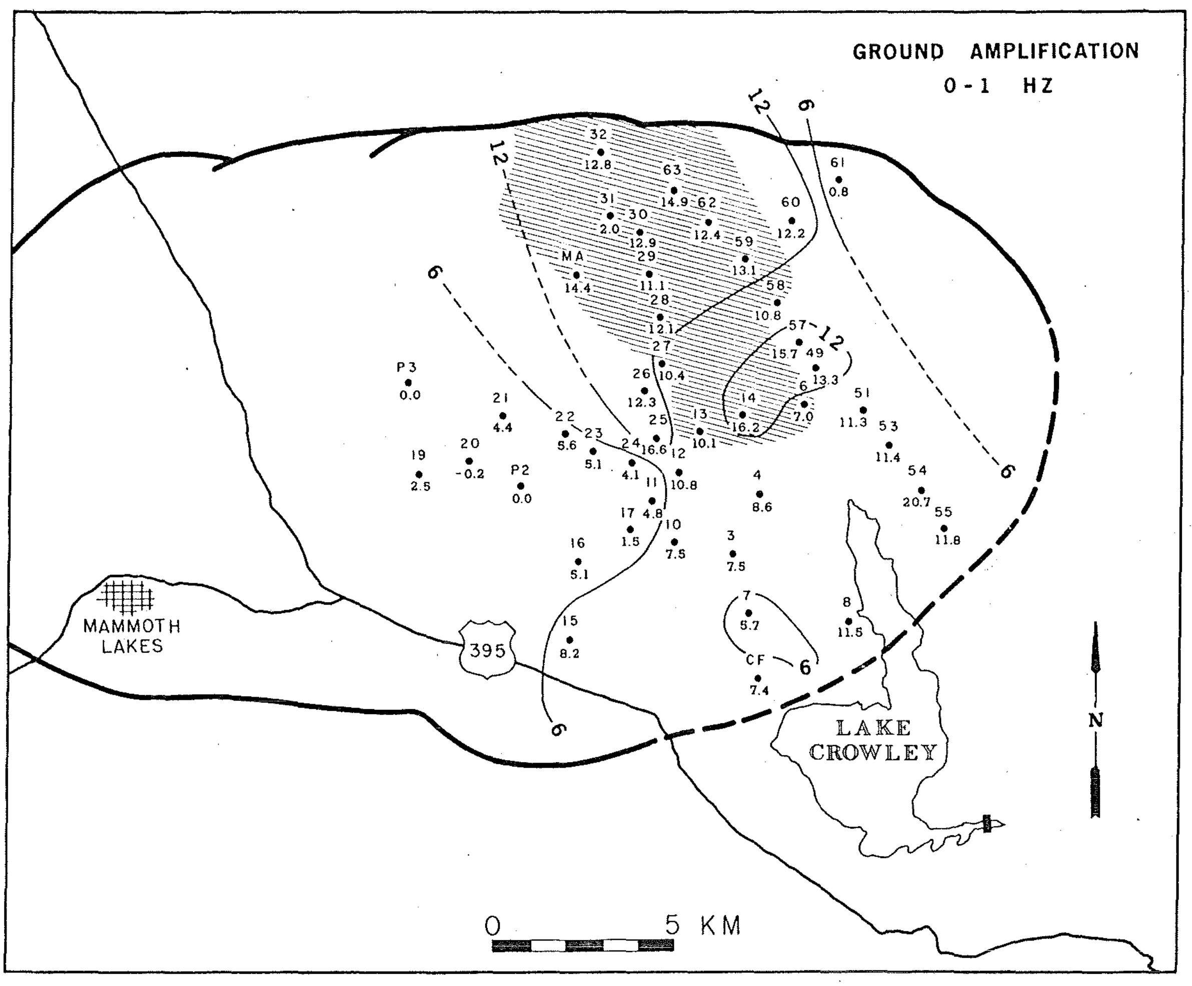

Fig. 6*a*. 0- to 1-Hz band.

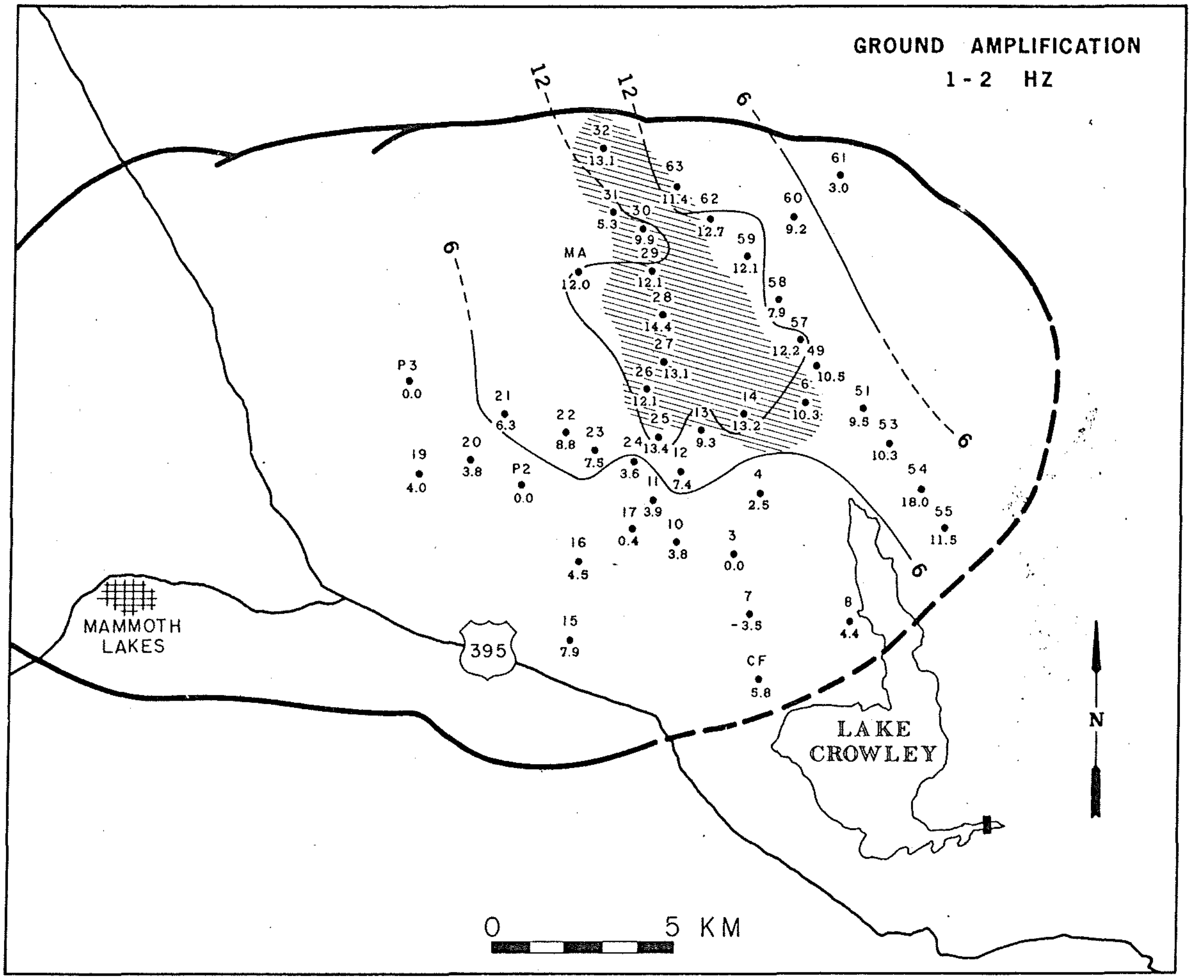

Fig. 6b. 1- to 2-Hz band.

Fig. 6. Ground amplification contours of earthquake waves. Dots are station locations, station identification is shown by numbers above dots, ground amplification, in decibels with respect to P2 or P3, is shown below dots, and the contour interval is 6 dB. Relative noise levels are above 18 dB in the hatched area.

about 12 dB at stations 59 and 60 relative to the reference station P3 in the frequency band of 0–2 Hz. The values at frequencies greater than 2 Hz are not relevant because at these frequencies the seismic noise is the dominating influence. The seismic noise spectra at these stations, using quiet night samples, are shown for comparison with event spectra. (These samples were not taken immediately prior to the event.) It is quite clear from the noise spectra at 59 and 60, in the 0- to 2-Hz band, that the seismic noise is at least 20 dB higher than that at P3 (Figure 5*a*). Spectra at stations P2, 13, and 14 using the NTS event and giving good signal to noise ratios across the whole spectral band show ground amplification at 13 and 14 to be about 10 dB. The ratio of noise at stations 13 and 14 to the ratio at P2, however, is over 30 dB.

Spectral peaks are found both in the event ratios (ratio of spectrum at any station to spectrum at reference station for seismic waves from a particular event; also called ground amplification) and in the noise ratios (ratio of spectrum at any station to spectrum at reference station using noise samples taken during the same time interval), but their frequencies and amplitudes are found to be different. The frequencies at which the peaks occur also vary somewhat from profile to profile owing to difference in location or because different seismic events are used. The average ground amplification in the 0- to 1- and 1- to 2-Hz bands seems to have a reasonably smooth spatial variation (Figures 6*a* and 6*b*); this indicates that we have not seriously erred in using several seismic events recorded at different locations to arrive at a composite picture of seismic ground amplification in Long Valley.

Comparison of the spatial distribution of ground amplification in the 0- to 1- and 1- to 2-Hz bands (Figures 6*a* and 6*b*) with the spatial distribution of noise ratios (Figures 3*a* and 3*b*) shows clearly that for each frequency band the two distributions are quite similar. However, in the anomalous region, the noise ratios are higher by 6–9 dB in the 0- to 1-Hz band and by 12–15 dB in the 1- to 2-Hz band.

EVIDENCE FOR A NOISE SOURCE

Difference between ground amplification and noise ratio. Our main clue for proving that the noise anomaly is not caused by amplification of regional background noise, but by a local noise source in the vicinity of the anomaly, is derived from the observed difference between the ground amplification and noise ratio values. More examples of this phenomenon will now be presented. For the profile of stations 10–14, near the center of the eastern half of the caldera, there is a rapid increase in noise level, by about 12 dB in the 0- to 1- and 1- to 2-Hz bands. The gradient of noise level is very sharp within 2 km between stations 12 and 13 (Figure 3). The ground amplification and noise ratio spectra at stations 10–14 (Figure 7)

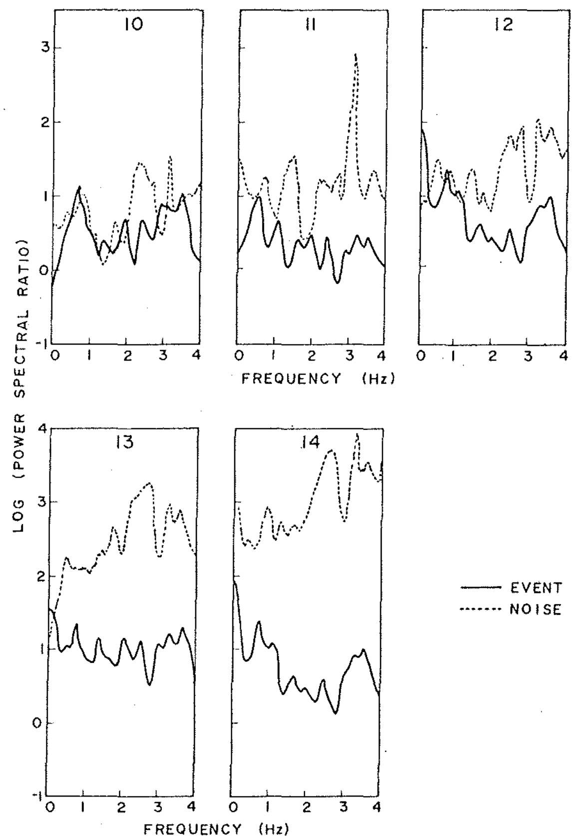

Fig. 7. Comparison of ground amplification spectra (solid line) and noise ratio spectra (dashed line) at stations 10, 11, 12, 13, and 14. P2 is the reference station.

show clearly that the two phenomena are not related in a predictable fashion. For example, at station 10 the two curves are similar except between 2 and 3 Hz where the noise is higher by about 10 dB. The peaks near 1 Hz are similar for noise and event ratio. At station 11 the two curves are distinctly different, the noise ratio being higher than the event ratio. Peaks can be seen in both the curves, but they occur at different frequencies and have different values. At station 12 the noise curve is significantly higher than the event curve above 1 Hz. The most spectacular difference between the ground amplification and the noise ratio, however, occurs at stations 13 and 14. It appears that either the mechanism by which the noise waves are amplified is entirely different from the amplification of seismic waves or a noise source that enhances the noise levels is present in the vicinity of station 13.

Another profile of stations across the noise anomaly from station 61 near the northeast edge of the caldera to station MA, near the center of the northern half of the caldera, shows that the noise ratios are definitely higher than the ground amplification (Figure 8). For this profile, unlike the previous profile where ground amplification values could be calculated throughout the spectra because of good signal to noise ratio, computations are valid only up to 2 Hz.

To compare theoretically the amplification of seismic noise in sedimentary basins with the amplification of earthquake waves, knowledge of the wave types involved in seismic noise is essential. More work is needed in this area and possibly also empirical studies in basins free from noise sources. In the present instance we could not find another water-saturated alluvial basin of the type found in Long Valley. However, some data are available from Owens Valley, about 50 km south of Long Valley, where we operated 10 stations for 1 night (Figure 9). The experiment was mainly intended to understand the generation and propagation of river-generated noise. One good teleseism was recorded during this period, and we were able to make some ground amplification calculations. The river noise is at frequencies above 6 Hz and cannot be detected beyond 1 km from the river. There was a clear spectral peak in the 2- to 4-Hz band, indicating what we infer to be an extraneous noise source associated with the town of Bishop, about 3 km northwest of the area where our stations were operated. All ground amplification values are with respect to station 64, on hard ground (Figure 10). The ground amplification and noise ratio spectra are in general within 6 dB of each other. The average values (indicated in Figure 10) in the 0- to 1- and 1- to 2-Hz bands are more or less alike for event and noise ratios. It is to be noted here that although our experimental area in Owens Valley has about 0.25 km of younger Cenozoic deposits and 0.75 km of older deposits overlying pre-Tertiary rocks (based on earlier seismic and gravity surveys [*Pakiser et al.*, 1964]), it is not like the water-saturated alluvium in Long Valley. The relative ground amplification and noise ratios in Owens Valley are similar to those at some of the stations in Long Valley (like station 10, Figure 7), which are outside the main peak of the noise anomaly. But ground amplification in Long Valley at stations within the noise anomaly (Figures 6*a* and 6*b*) is less than the noise ratios at these stations (Figures 3*a* and 3*b*) by at least 12 dB. The Owens Valley data, however, should not be taken as definite evidence that amplification of seismic waves produced by noise and events is about the same in sedimentary basins. They only indicate that such a situation is quite plausible, in which case, one possible explanation for a big difference between event and noise ratios is the presence of a noise source in the neighborhood of stations where such a difference was measured.

Possible noise sources. River and stream noise can be eliminated as a possible source of the noise anomaly in Long Valley because in Owens Valley the fast flowing river seems to be generating noise only at frequencies above 6 Hz, and even this high-frequency noise attenuates rapidly with distance. Comparison of spectra of seismic noise recorded at station 66, very near the Owens River, and at stations 67 and 68, 1 and 2 km

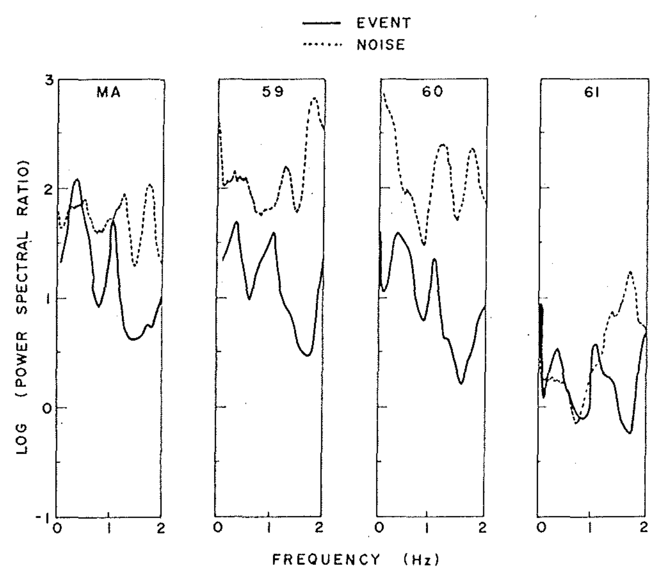

Fig. 8. Comparison of ground amplification spectra (solid line) and noise ratio spectra (dashed line) at stations MA, 59, 60, and 61. P3 is the reference station.

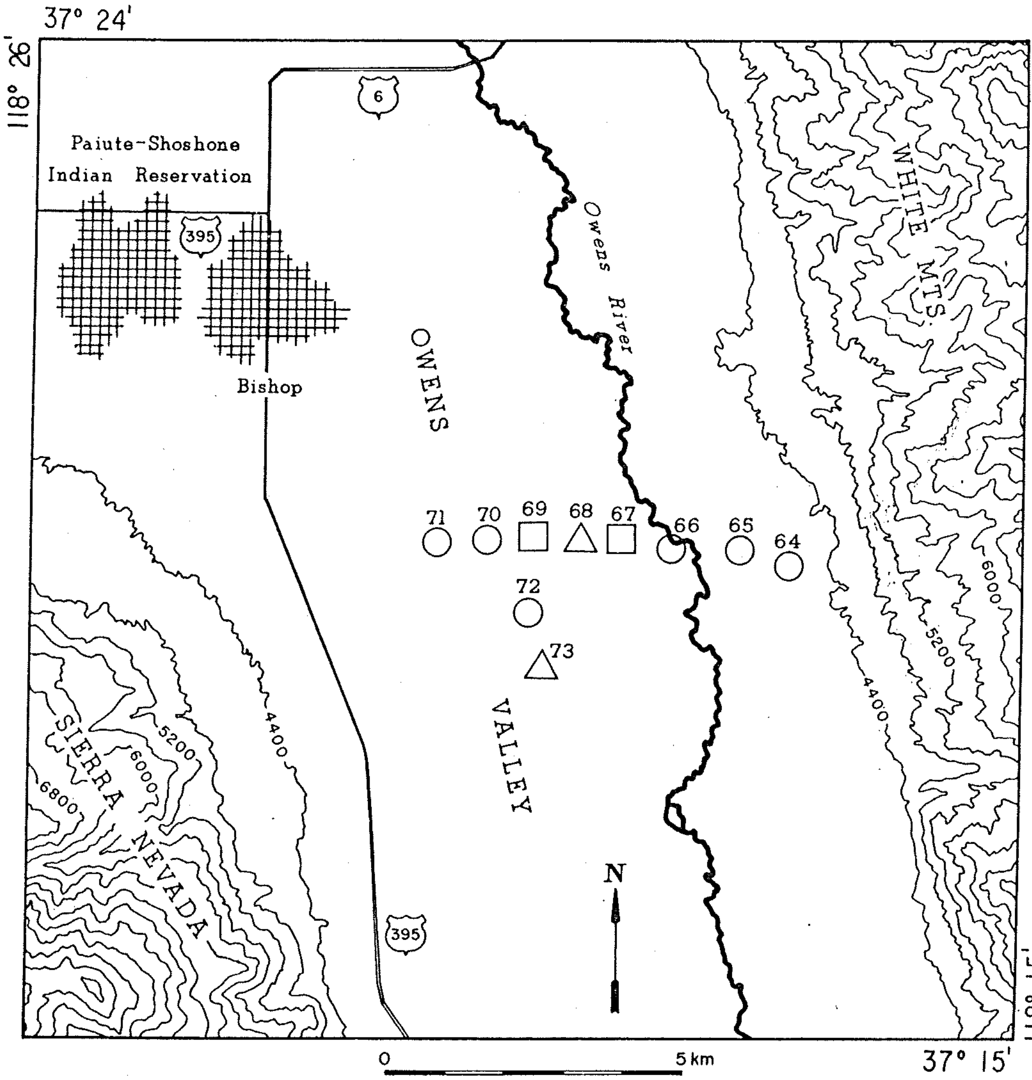

Fig. 9. Location of seismic stations in Owens Valley, near Bishop. Circles, squares, and triangles show single-component, three-component, and three-element array stations, respectively. Numerals are station identification.

from the river, shows that the high-frequency (above 6 Hz) noise drops by about 12 dB in 1 km (Figure 11). The rest of the spectra are not significantly different at these stations. At Long Valley the main Owens River and the associated streams are smaller and flow less rapidly than the river in Owens Valley. Hence we think it is highly improbable that a large noise anomaly like the one observed at frequencies below 4 Hz can be a result of river noise.

During our experiment, several hundred cattle were present along the grasslands by the river and near Lake Crowley in Long Valley. Because the noise anomaly is approximately located in this area, we thought that the cattle might be the possible source of seismic noise in Long Valley. We reoccupied eight of the stations for 3 nights during November 1974, when most of the cattle were gone and those remaining were mainly confined to one area near station 29 (Figure 12). In addition to the reference station P2 and the quiet station 61, six locations (11, 13, 27, 29, MD, and 59) that showed high noise levels in 1973 were reoccupied (Figure 12). The average noise levels (relative with respect to P2) in three frequency bands, based on 1-hour data recorded at night, and their comparison with the 1973 levels are also shown in Figure 12. In general, the noise levels are lower in November 1974 than in June 1973. The noise levels in the 0- to 1-Hz band are similar in 1973 and 1974. In the 1- to 2-Hz band the largest drop of about 7 dB occurs at station 27, the reduction at the other stations being about 3–6 dB. In the 2- to 4-Hz frequency band there is a general drop of about 6–12 dB in noise level. The only station that retains the 1973 level in this frequency band is 29. Since station 29 is very close to the area where 500 cattle were confined in November 1974, it is likely that the noise in this frequency band might be generated by cattle. If the noise in the lower-frequency bands is also due to cattle, it is difficult to understand how stations 13 and 59, about 5 km from the area of cattle concentration in 1974, can have similar noise levels to those at station 29 in the cattle zone. The levels at these stations have changed very little between 1973 and 1974. About 130 cattle were near station 13 during the first night recording in November 1974 but were removed before recording started on the second night. At this station there was virtually no change in noise levels except in the 2- to 4-Hz band. In this frequency band the noise level during the second night is less by about 4 dB than that during the first night, a phenomenon that can be attributed to removal of cattle from the area where the station is located. But the noise level decreased again by about 3 dB between the second and third nights.

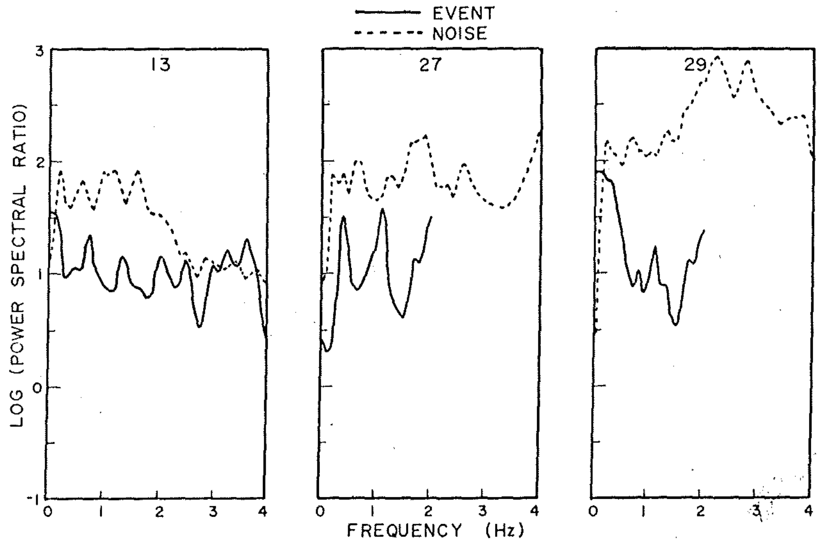

Fig. 14. Comparison of ground amplification spectra (solid line) and noise ratio spectra (dashed line) at stations 13, 27, and 29 using 1974 data. P2 is the reference station.

waves in Imperial Valley, California [*Iyer*, 1974], a cross-spectral technique was used to compute coherence and phase difference between records from an array at several frequencies. Such a technique was tried by using the Long Valley data, but the picture that emerged was extremely confusing. Two prerequisites for the success of the cross-spectral technique are that (1) the spacing between array elements should be much less than half the wavelength of the seismic signal being processed, so that the phase differences can be determined uniquely, and (2) the records should be 'stationary,' meaning that the phase difference between channels does not change within the sample being analyzed. In Long Valley the average group velocity of seismic noise waves is about 140 m/s (see below). Phase velocity and wavelength estimates were not possible. Hence we are not sure if condition (1) is met for the array spacing of 106.7 m. Visual examination of records showed that the phase differences between wave trains in the array changed even within short samples. Hence condition (2) is not satisfied. Because of these factors a different technique of direction and velocity estimation using array data was tried in Long Valley. Short sections (3 s) of data from pairs of array channels are correlated for varying lags. The lag at which maximum correlation occurs is a measure of the phase difference between wave trains and hence is an estimate of the time taken by the wave train to travel between the two elements of the array. Two values of phase difference can thus be obtained by correlating records from the central element of the array with records from the first and third elements, and by using these values, velocity and azimuth of wave travel can be computed by simple trigonometry. The method has the advantage that correlation is done over a whole train of waves in addition to individual peaks and troughs. After experimenting with different time windows, we decided to use 3-s segments of data for correlation. The time window was moved in steps of 1 s so that successive segments overlapped to ensure that no well-formed whole wave train was missed. The analysis was carried out for filtered data in frequency bands of 0–1, 1–2, and 2–4 Hz.

Results using a few seconds of data at several stations show that although velocity measurements are very stable, the azimuths are widely scattered. To build up sufficient statistics, we analyzed 10 min of data for a selected number of arrays in and around the noise anomaly. At each station, 540 velocity and azimuth values are computed for each frequency band. The surprising result is the persistence of the low group velocity,

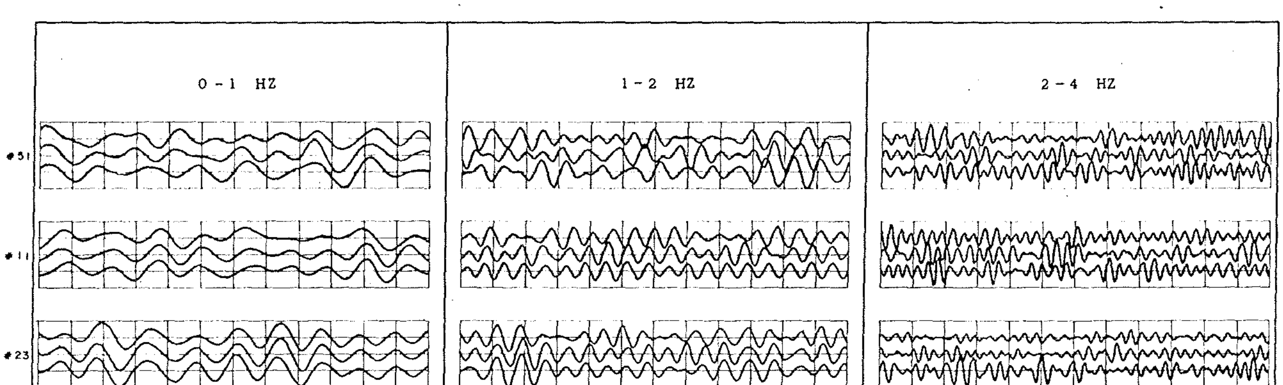

Fig. 15. Typical filtered noise samples at array stations 11, 23, and 51.

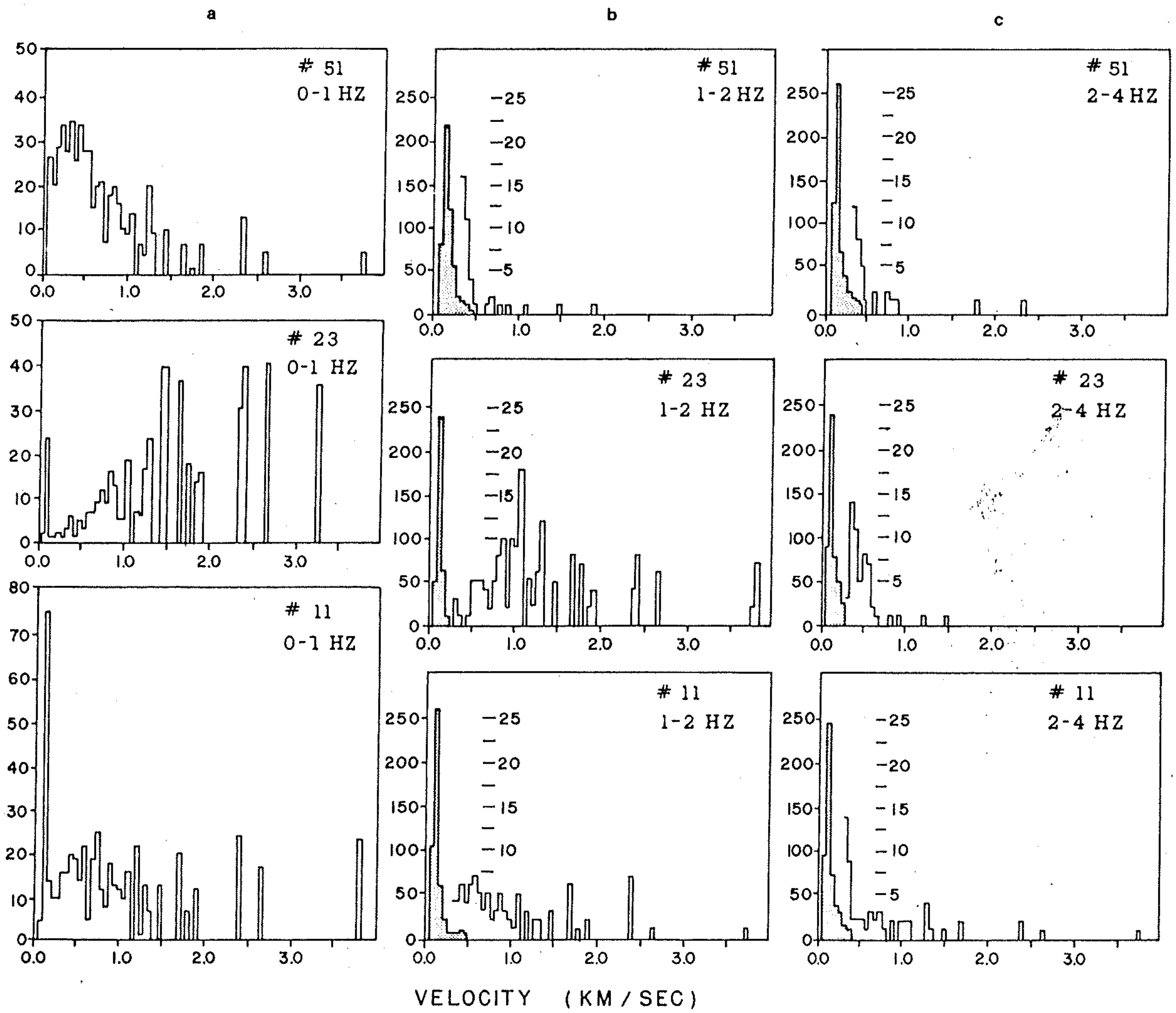

Fig. 16. Frequency distribution of velocities at stations 51, 23, and 11 for (left) 0- to 1-Hz band, (middle) 1- to 2-Hz band, and (right) 2- to 4-Hz band. Dotted area outlines histograms with normal scale shown to the left. Open area outlines histograms for the higher velocities with magnified scale shown to the right.

around 0.14 km/s, in the 1- to 2- and 2- to 4-Hz bands and the velocity of about 0.45 km/s in the 0- to 1-Hz band at all the stations. At the group of stations along the southern edge of the noise anomaly, however, there are many velocity values that are substantially higher than the average values of 0.14, particularly in the 1- to 2-Hz band. Typical velocity distributions using data in the three frequency bands are shown in Figure 16.

In the 0- to 1-Hz band the velocity distributions at eight of the 11 stations are similar to those (shown in Figure 16*a*) at station 51. The exceptions are stations 11 and 24, where the values are distributed over a wide velocity range, and station 23, where the distribution peaks near 1.5 km/s (Figure 16*a*). In the 1- to 2-Hz band the largest concentration of velocity values occurs between 0.1 and 0.15 km/s at all stations, as shown by the examples in Figure 16*b*. At stations 11, 12, 23, and 24, however, secondary peaks indicate the presence of higher-velocity waves (as shown for station 11 and 23 in Figure 16*b*). In the 2- to 4-Hz band (Figure 16*c*) the low-velocity parts of the distributions are identical to the velocity distributions in the 1- to 2-Hz band. The evidence for higher-velocity arrivals, however, is not clear. We believe that the consistent low velocity of around 0.15 km/s seen very clearly in the 1- to 2- and 2- to 4-Hz band and to some extent in the 0- to 1-Hz band (note sharp peaks in the 0.1- to 0.15-km/s range in the velocity distribution of Figure 16) is associated with the fundamental mode of excitation of the soft sedimentary layer. Since our measurements are based on correlating whole wave trains rather than peaks and troughs of individual waves, the resultant estimates give group velocities rather than phase velocities. The excitation probably corresponds to the Airy phase associated with a stationary value of group velocity of surface wave propagation in layered media [*Ewing et al.*, 1957, chap. 4]. Surface wave trains with similar velocities have been observed in explosion seismograms in Long Valley [*Hill*, 1976]. Even though it is difficult to make an exact estimate of the thickness of the sedimentary layer that is responsible for these waves, it is possible to infer that the material is only a few tens of meters thick. The characteristic velocity peak around 0.5 km/s in the 0- to 1-Hz band found at most of the stations is probably due to these waves (which have longer wavelengths than those at higher frequencies) 'seeing' a thicker layer overlying the soft upper layer.

At stations 11, 12, 23, and 24, southeast of the noise maximum in Figure 3*b*, seismic waves with velocities in the range of 0.9–1.5 km/s are found in addition to the low-velocity waves described earlier. If these high velocities are due to higher modes of propagation, they should have been seen at all

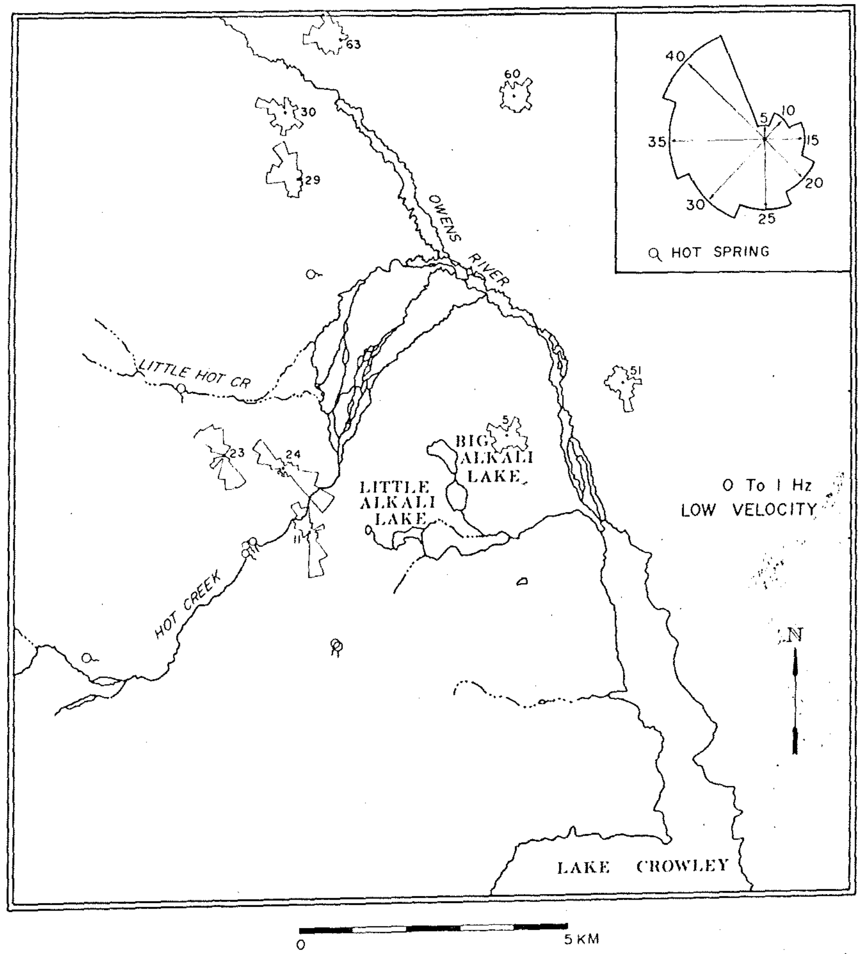

Fig. 17*a*. Spatial display of frequency distribution of azimuths of low-velocity noise in the frequency band 0–1 Hz.

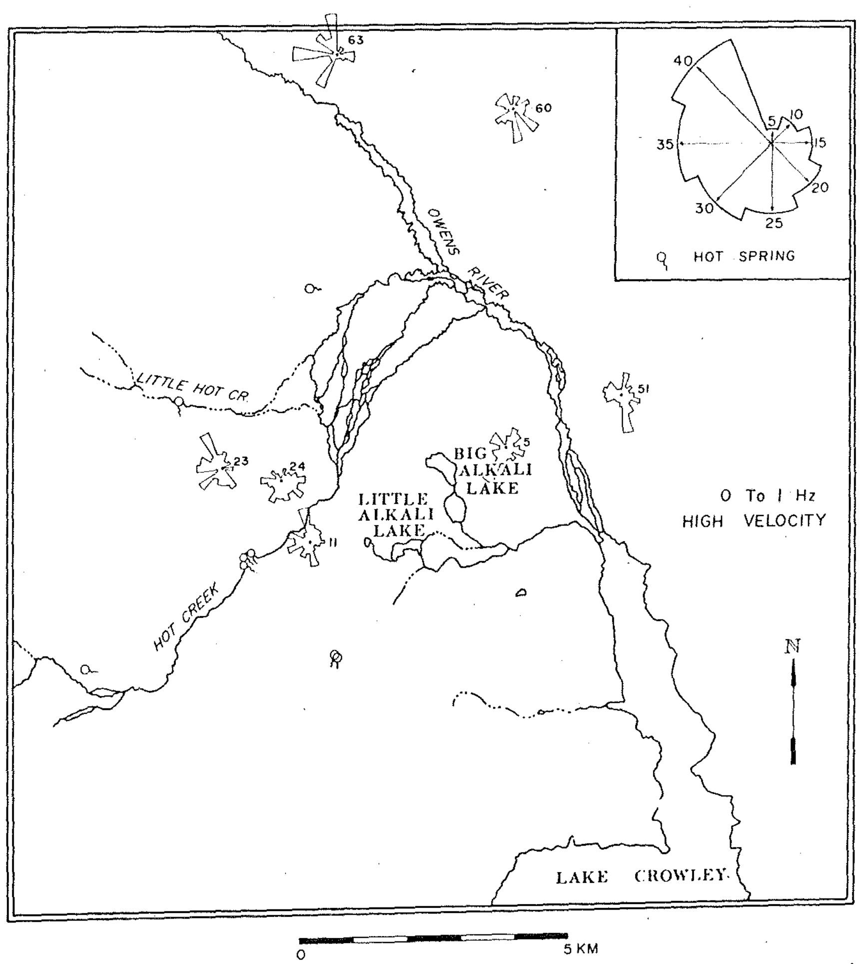

Fig. 17*b*. Spatial display of frequency distribution of azimuths of high-velocity noise in the frequency band 0–1 Hz.

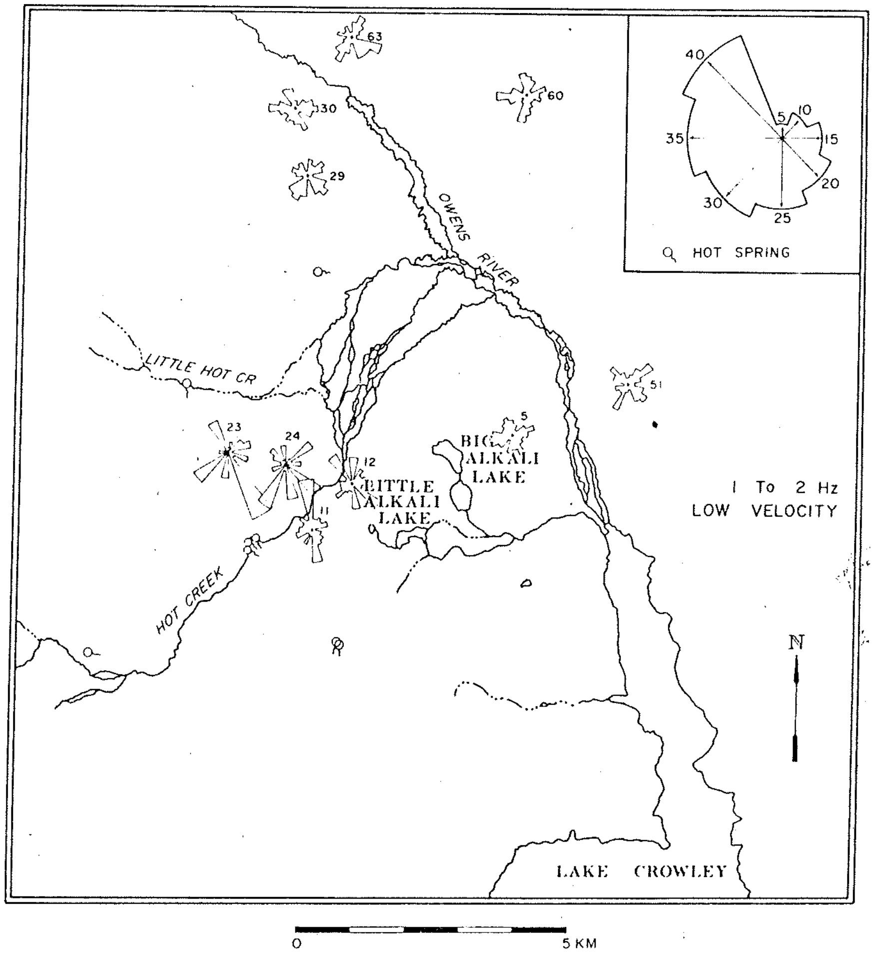

Fig. 18*a*. Spatial display of frequency distribution of azimuths of low-velocity noise in the frequency band 1–2 Hz.

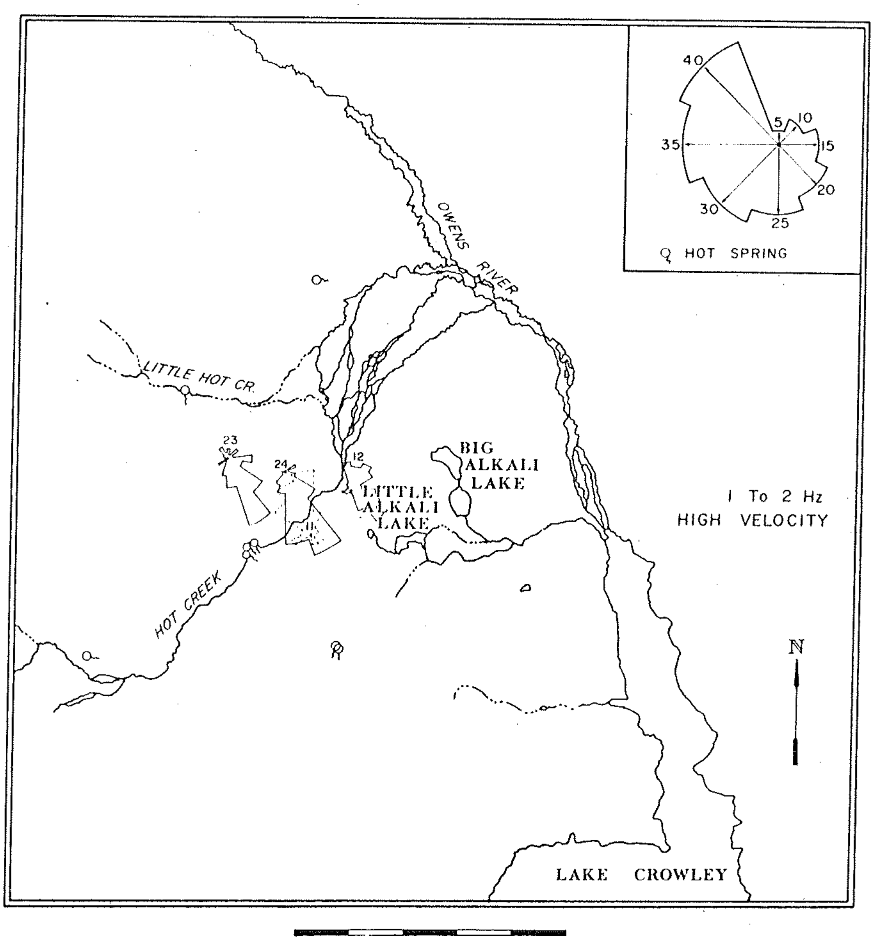

Fig. 18*b*. Spatial display of frequency distribution of azimuths of high-velocity noise in the frequency band 1–2 Hz.

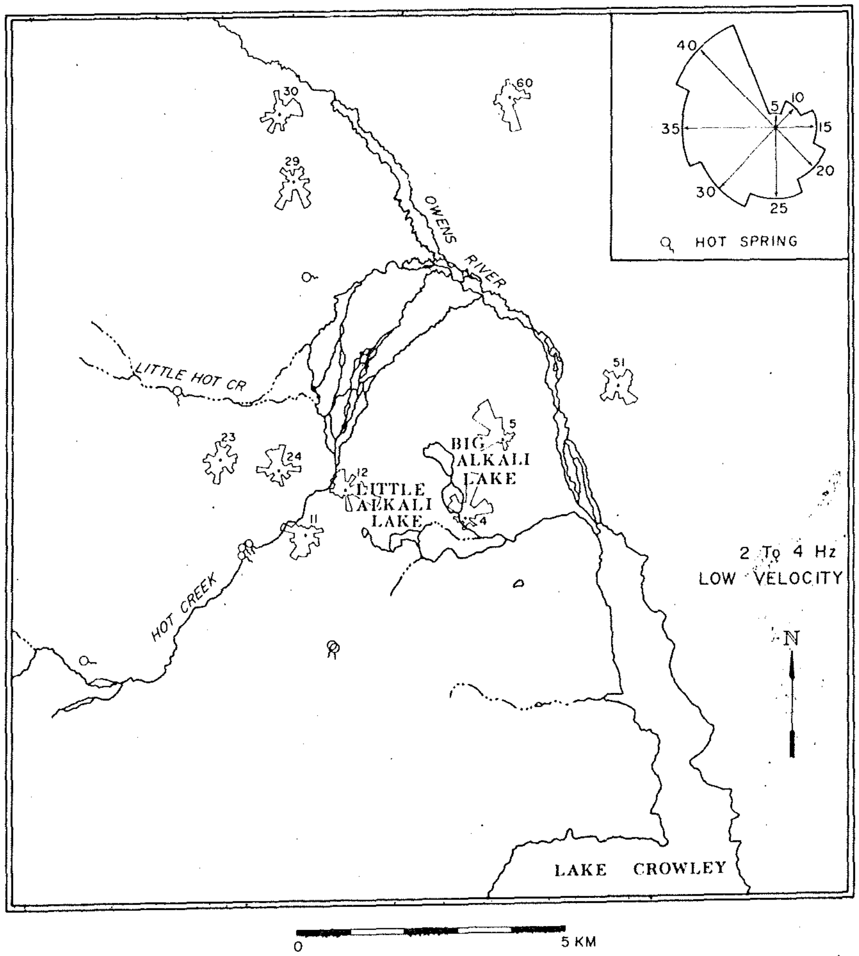

Fig. 19*a*. Spatial display of frequency distribution of azimuths of low-velocity noise in the frequency band 2–4 Hz.

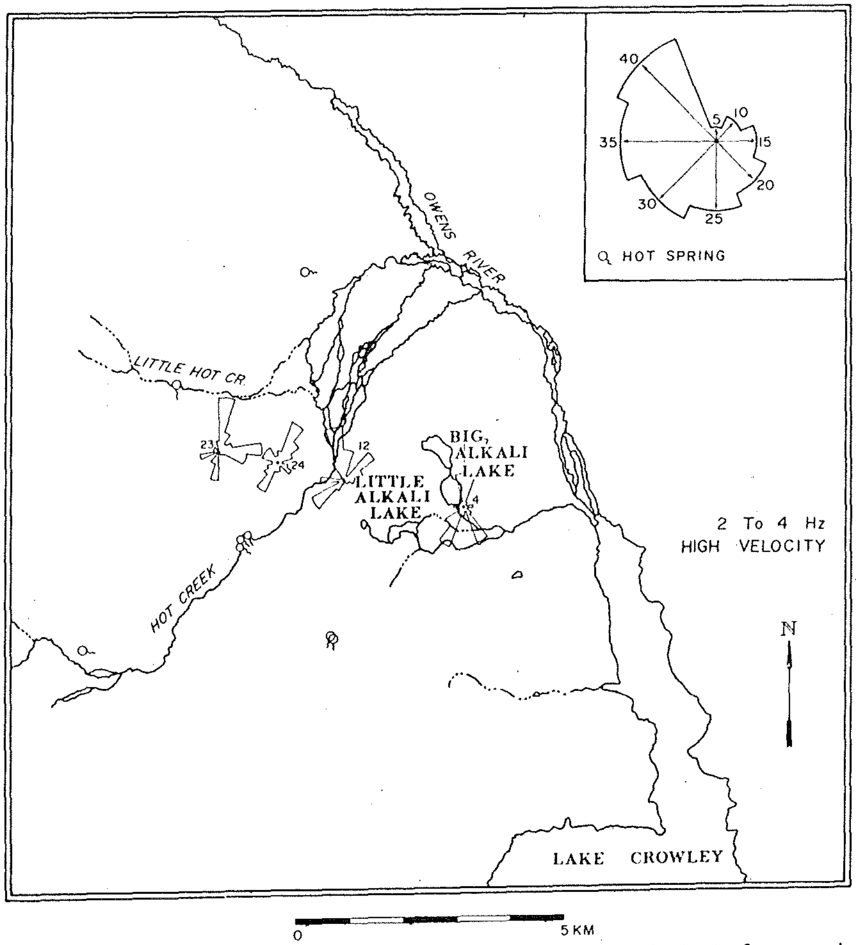

Fig. 19*b*. Spatial display of frequency distribution of azimuths of high-velocity noise in the frequency band 2–4 Hz.

stations over the sedimentary basin. Note that these four stations are in the part of Long Valley with many surface expressions of geothermal phenomena. We think that a geothermal source under these stations could generate seismic waves that in a soft sedimentary basin would travel directly to the stations at a higher apparent velocity than the horizontally propagating surface waves excited by the same source. It is interesting to note that the high-velocity values are close to the P wave velocities of 1.5–2.0 km/s in the upper layers of the east part of the caldera [*Hill*, 1976].

Direction studies. We have plotted histograms of distribution of azimuths for low-velocity (less than 1 km/s for 0- to 1-Hz band, less than 0.3 km/s for 1- to 2- and 2- to 4-Hz bands) and high-velocity data (where at least 50 values are available) at the array locations in Figures 17, 18, and 19.

0- to 1-Hz band (Figures 17a and 17b). Stations 29, 30, and 63, located near the north central part of the caldera, indicate the presence of a broad source of low-velocity seismic noise in this band toward northwest. Stations 11, 23, and 24, in the south central part of the caldera, point to sources in the northwest and southeast directions. The northwestern source of noise may be associated with ocean waves along the coast, the cause of persistent seismic noise (microseisms) with predominant frequencies around 0.13 Hz [*Haubrich*, 1967]. No doubt there are various other sources of noise in the area as shown by the low-velocity distribution at stations 60, 5, and 51 and the high-velocity distributions shown in Figure 17*b*.

1- to 2-Hz band (Figures 18a and 18b). Azimuthal distributions of low-velocity arrivals show a multiplicity of sources with no clear evidence of a concentrated noise source under the noise level peak indicated by the anomaly. The high-velocity noise observed at stations 11, 23, and 24, however, indicates the presence of a noise source between 11 and 24. Station 12 shows a wide source toward the east where the peak of the noise anomaly is present. If the high velocities are interpreted as a result of noise sources beneath the stations, the evidence shown here can be taken to indicate that geothermal noise sources are present in the vicinity of this cluster of stations.

2- to 4-Hz band (Figures 19a and 19b). The low-velocity distributions indicate the presence of many sources. High velocities were clearly seen in this frequency band only at station 12. At stations 4, 23, and 24 the evidence for high velocities was not clear, although we have shown the results from these stations in the figure. The velocity distributions point to sources to the northeast (toward the peak of the noise anomaly) and the southwest. As we showed earlier, the noise in this frequency band is probably most susceptible for contamination by nongeothermal local sources, and we are not sure that velocity distributions can be given any meaningful interpretation.

DISCUSSION AND CONCLUSIONS

The evidence presented shows the following:

1. A noise anomaly exists over most of the east half of the Long Valley caldera.
2. The anomaly is over an area of soft sedimentary material that can amplify seismic ground motion from regional and teleseismic sources by almost 12 dB.
3. The noise anomaly is about 12–18 dB higher than can be explained by postulating amplification of regional background noise by the sedimentary basin by the same factor as in the case of the amplification of earthquake waves.
4. A few measurements taken 18 months later, in November 1974, showed that the noise levels had decreased by about 6 dB in the 1- to 2-Hz band and 12 dB in the 2- to 4-Hz band. This change in noise level reduces the margin between the noise anomaly and ground amplification. In spite of this difficulty the difference between the noise and event amplification can be explained by the presence of a noise source generating seismic waves of about 2 Hz or less in frequency. This might very well be a geothermal noise source. The higher frequency waves could be generated by cultural sources or cattle.

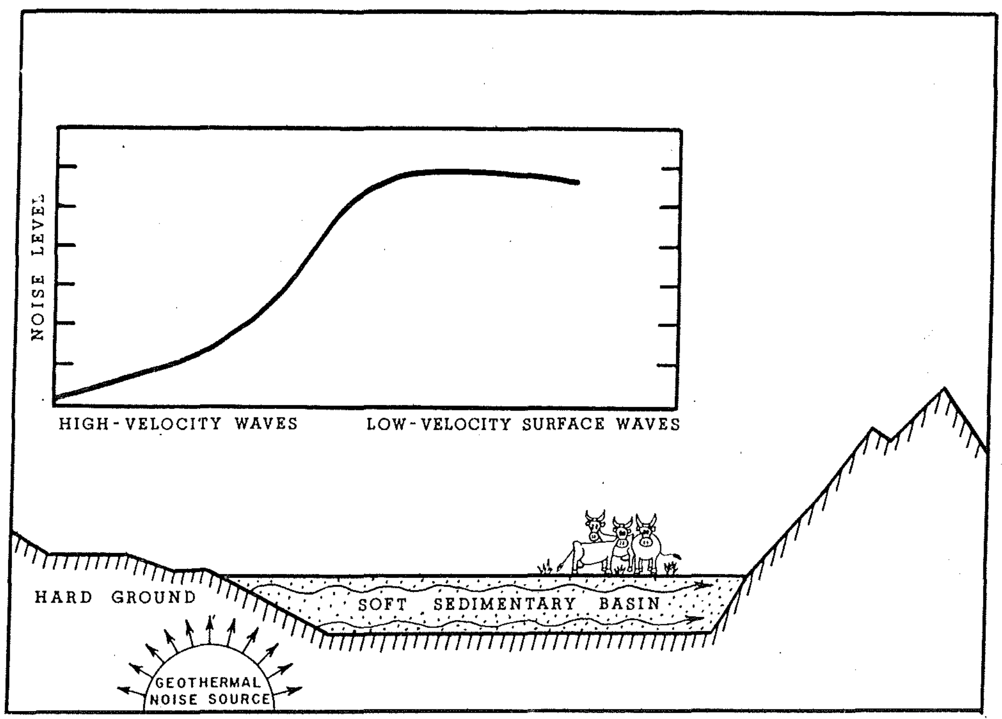

Fig. 20. A schematic model to illustrate how a geothermal noise source under hard ground can create high seismic amplitudes over an adjacent sedimentary basin. Arrows around noise source show seismic waves radiating from it. They are trapped by the sedimentary basin and propagate horizontally as surface waves as shown by the wavy lines. The top curve shows spatial variation of noise level at the surface.