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LAMONT-DOHERTY GEOLOGICAL OBSERVATORY
OF COLUMBIA UNIVERSITY
PALISADES, NEW YORK 10964

Long-Period Seismological Research Program

Final Report

Contract F44620-70-C-0038

30 April 1971

Sponsored by
Advanced Research Projects Agency
ARPA Order No. 1513

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Four long-period, high-gain, three-component seismograph systems were designed, constructed and installed in Alaska, Australia, Israel, and Thailand. A fifth station is being installed in Spain. These instruments have peak response of 500,000 at periods of 35 to 45 seconds. This high sensitivity is achieved by isolating the seismometer from barometric changes, by electronically filtering out the six-second mocroseisms and by shaping the instrument response to correlate with a natural minimum in the earth-to-noise spectrum. Data from Alaska, Australia, and the prototype instrument in New Jersey are sufficient for detecting Rayleigh waves from all earthquakes with a body wave magnitude of from 3.8 at distances of about 0 to 15° to 4.7 at distances greater than 100°. The minimum detectable magnitude is also a function of geographic location. A minimum is found in the spectral amplitude of earth noise between 30 and 40 seconds at all sites. The lowest level of the noise was observed in Thailand. G waves and inversely dispersed Rayleigh waves are commonly observed for events as small as $m_b \sim 5$. Free oscillations lasting for over 24 hours were observed following an event of magnitude 7.3.

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ABSTRACT

Four long-period, high-gain, three-component seismograph systems were designed, constructed and installed in Alaska, Australia, Israel, and Thailand. A fifth station is being installed in Spain. These instruments have peak response of 500,000 at periods of 35 to 45 seconds. This high sensitivity is achieved by isolating the seismometer from barometric changes, by electronically filtering out the six-second microseisms and by shaping the instrument response to correlate with a natural minimum in the earth-noise spectrum.

Data from Alaska, Australia, and the prototype instrument in New Jersey are sufficient for detecting Rayleigh waves from all earthquakes with a body wave magnitude of from 3.8 at distances of about 0 to 15° to 4.7 at distances greater than 100°. The minimum detectable magnitude is also a function of geographic location. A minimum is found in the spectral amplitude of earth noise between 30 and 40 seconds at all sites. The lowest level of the noise was observed in Thailand. G waves and inversely dispersed Rayleigh waves are commonly observed for events as small as $m_b \approx 5$. Free oscillations lasting for over 24 hours were observed following an event of magnitude 7.3.

I. Purpose of the Research

1. To complete development and design of a new high-gain, long-period seismograph system with peak gain of about 500,000 at 40 to 50 seconds.

2. To construct five of these systems and install them in Alaska, Australia, Israel, Spain, and Thailand for the purpose of testing this equipment under different environmental conditions.

3. To operate these five systems and analyze the data in the following areas:

a. Determine the threshhold and the behavior of the long-period amplitude spectra at small magnitudes and different focal depths.

b. Study the spectral differences of long-period waves.

c. Investigate the influence of source region and source type on the azimuthal patterns of radiated energy.

d. Investigate the travel path anomalies and azimuthal variations.

The main effort under this contract was devoted toward the construction and installation of the equipment. Data analysis was only possible during the last few months of the contract period while problems with the instruments were still being worked out.

II. Instrumentation

The general and detailed descriptions of the instruments are given in a technical report entitled "High-Gain, Long-Period Seismograph Station Instrumentation" appended as part of this final report. Major components for eleven sets of

instruments were purchased under this contract but only five sets were installed. The other instruments were shipped to places designated by the project scientist.

III. Installation

The detailed descriptions of the instrument locations and installation procedures are contained in technical reports entitled "High-Gain, Long-Period Seismograph Station Installation Report" for the following stations: Fairbanks, Alaska by Andrew J. Murphy; Charters Towers, Australia by John M.W. Rynn; Eilat, Israel by Tracy Johnson; and Chiang Mai, Thailand by Andrew J. Murphy. Copies of these reports are appended to this final report.

Installation of the station in Toledo, Spain was delayed because the necessary approval from the Spanish government was not received for construction to begin until March, 1971. Vault construction was begun in early April and installation should be completed in June, 1971.

IV. Data Collected

The instruments generally have been operating well since installation. In the period of about four months we were able to install four systems using installation techniques developed at Ogdensburg and in most cases draw usable records immediately. A certain number of problems had to be resolved during the first few months of operation as was well anticipated for instruments of this complexity. The greatest problems have been with the

digital recorders as could be expected since these instruments had not been field tested prior to this project. These digital system failures should be considerably reduced as the "burn-in" time increases and when uninterruptable power supplies are installed at each station by summer 1971. The data collected during the first few months of operation is summarized in Table I together with brief comments outlining problems encountered.

TABLE I

Station	Beginning of Analog Recording	Beginning of Digital Recording	Remarks
Charters Towers, Australia	25 Sept 1970	25 Sept 1970	E-W component inoperative until 1 Jan 1971 because of problems with seismometer and cabling. At the present time the E-W high gain is still very noisy. All tapes beset with power failures averaging 5 per week. From 24 Jan 1971 to present time tape data unusable because of problems with ADC.
Eilat, Israel	5 Dec 1970	5 Dec 1970	Analog records received at LDGO to date are only up to 31 Dec 1970. Digital tapes up to 28 Mar 1971 have been received at LDGO. Vertical inoperative 12 to 20 Dec. The N-S component seismometer period dropped to 15 sec after installation.
Chiang Mai, Thailand	10 Dec 1970	1 Feb 1971	Digital recorder was not operational 23 Feb to 20 Mar 1970 because a power supply failed.
Fairbanks, Alaska	26 Sept 1970	27 Sept 1970	N-S and E-W high-gain components were excessively noisy until 25 Jan 1971 due to problems with the seismometers and galvanometers. Digital tapes for all times except 11 Oct 1970 to 18 Nov 1970 and 9 Feb 1971 to 25 Feb 1971 have power failures that average one per 20 days. Digital tapes for the*

*period 18 Nov 1970 to 24 Jan 1971 are unusable because of failure of the power supply system in the tape recorder.

V. Data Reduction Techniques

A number of computer programs were developed for using the digital data. The following is a brief summary of the existing programs and support packages used in the analysis of the high-gain data.

a. Tape copying: Before being forwarded to Texas Instruments, the source data tapes are copied onto what we call edited tapes. In this operation the data are translated from the format of the data-logging device into a Fortran compatible format. Check bit errors are detected and rectified. The output records on the edited tape are of a standard, uniform length, regardless of the input record length (which is affected by the sampling rate, the number of A and B channels, power failures, tape errors, operator errors, etc.). The edited tapes, written at 800 bpi, have about 50% data compression and are much faster to work with than the original source tapes.

b. Data editing: Both the source tapes and the edited tapes can be scanned for interesting events using the data editing package. This is an interactive program that allows selected channels to be displayed on a cathode-ray tube. The gains and time scale can be modified at will by the operator. Using this package, the operator can quickly search a data tape for a desired event, examine it, photograph it, plot in on a hard copy plotter, and, most important, transmit the selected channels to a large volume disk file. In this

way, the operator can build up a disk file of interesting events for subsequent treatment. Because the disk file is a random access storage device, the operator can prepare files of the same events from each of the high-gain stations and, in subsequent processing, achieve the effect of a multiplexed data tape. The disk file is large enough to store many events; there is room for 6 days continuous records of a single velocity channel, or a month of a displacement channel.

All the contents of the disk file are available for use by subsequent programs; the user can simply call for the events by name.

c. Data Analysis: Standard analytic techniques are programmed to use the data from the disk file. Power and cross-spectrum analysis, error detection and correction, filtering and plotting programs are examples. In a research environment it is deemed unnecessary, and in fact undesirable, to have too many analytic techniques "frozen" in the standard form. Hence, the programming support has been provided in a building block form. Individual subroutines perform the needed operations; fast Fourier transforms, recursive filtering, convolution filtering, fast convolution by transform products, smoothing followed by decimation, etc. In this way, a scientist with only a rudimentary knowledge of programming can easily develop and experiment with rather sophisticated signal processing techniques. To give an example, a matched-filter

could be built to seek events ressembling a master event by calling the capitalized subroutines: REAP, to fetch the master event; REVERS, to reverse its time sense; REAP, to fetch data to be filtered; FCON, to perform fast convolution; and PLOTR to plot the output. The last three steps could be repeated indefinitely.

By programming each building-block subroutine as efficiently as possible and by careful attention to sequential processing of the data, the limited capacity and speed of the IBM 1130 computer at Lamont does not prove to be a barrier, or at least not an insurmountable barrier, to surprisingly complex data processing. When a larger computer is needed, an IBM 360 on the Columbia campus is used.

VI. Results of the data analysis

Analysis of data from the newly installed high-gain seismograph stations at Charters Towers, Australia; Fairbanks, Alaska; Chiang Mai, Thailand; and Eilat, Israel in conjunction with data from the high-gain station at Ogdensburg was initiated on the following topics:

1. Ultimate detection levels of world-wide seismic events.

2. Discrimination between earthquakes and underground explosions using long-period body and surface waves.

3. The structure of earth noise at periods longer than 10 to 15 sec.

4. Excitation of mantle Rayleigh and Love waves as a function of magnitude, region, and focal depth.

5. Free oscillations.

Data analysis was generally limited to these topics because of the short time available after station installation and because these topics were considered to be the most immediately promising subjects that fall within the initial intent of the research. The results obtained to date come from both visual and digital analysis of the data.

Detection Levels for Surface Waves

The objective of this study is to determine the ultimate detection capabilities of the six high-gain stations for world-wide seismic events. The method used is to compare the number of events observed on the three-component high-gain seismograms during some time interval with the number of events reported by the United States Coast and Geodetic Survey (USCGS) for the same time interval.

At the present time the results in Table 1 are based on 230 hours of recording time at the high-gain stations at Ogdensburg, Charters Towers (CTA), and Fairbanks. The choice of this particular time period was dictated by the availability of the monthly listings of the USCGS and the overlapping of high-gain data. Recording at the Chiang Mai and Eilat sites did not start until December 1970.

The analysis method employed to date consists simply of visual scanning of the seismograms for body and/or surface waves. An event is considered as detected if body and/or surface waves are observed. Amplitude and period measurements are taken and are being used in a separate M_s-m_b study of world-wide events.

The most striking result in Table 2 is that a total of 198 separate events were detected by the three high-gain stations while only 117 events were reported by the USCGS. Thus, long-period surface waves were observed for 93 events not reported by the USCGS, while only 12 events reported by the USCGS were not observed by the three high-gain stations.

The total number of events divided by the number of days of recording yields a detection rate of 20 to 21 events/day or about 7500 events/yr for these three stations. It should be noted that this detection rate, 7500 events/yr, is a minimum number since the recording times chosen for analysis did not include any large shock (m_b>6.0) aftershock sequences that would substantially increase the number of events detected. Thus we have tested the capabilities of these three sites for relatively "quiet earth" conditions. The largest number of unreported (USCGS) events were observed at CTA, which probably results from the proximity of this site to the active trench systems of the southwest Pacific. As discussed later, however, the number of unreported events at

a given station (Table 2) may also merely reflect the relative noise levels at the recording sites.

Evernden et al. (1971) found that the Ogdensburg detection levels for Rayleigh waves from events in the Aleutians (Δ=60 to 70°) and the New Hebrides, Solomon Islands regions (Δ=120°) were m_b=4.4 and 4.5 respectively. The results in Table 3 show that with the high-gain stations at Australia and Alaska, the detection thresholds for events in these two regions have been substantially lowered, i.e., by 10 to 12 db. For instance, the station in Fairbanks can detect surface waves from m_b=3.8 Alaskan events up to 15° away and m_b= 4.2 for Rat Island events. The Australian station detects surface waves from m_b=3.8 events in the New Guinea, New Hebrides and Solomon Island regions. The significance of these very low thresholds can be appreciated when we recall that the high-gain stations at Eilat, Israel and Chiang Mai, Thailand, are 18 to 20° from locations of presumed underground explosions in Russian and China, respectively. There are not sufficient data (seismograms and monthly listings) presently available at Lamont from these two stations, especially Eilat, to determine thresholds for nearby regions. When these data become available, this study will be extended to include these two recording sites.

In the interim we are continuing analysis of the data from Ogdensburg, Charters Towers, and Fairbanks to fill in obvious

gaps in the world-wide coverage of detection thresholds. A paper describing these results is in preparation and will be submitted for publication in JGR.

A similar study is under way for long-period P wave detection thresholds at these three sites. While the present results are rather preliminary, in general the thresholds for P, S, and multiple S phases are approximately 0.5 m_b unit higher than the surface wave detection thresholds for a given region. Long-period S and multiple S phases are the most conspicuous body phases on the high-gain recordings. Since these waves are probably not subject to significant multipath effects, they could be used with matched filters for the observation of earthquakes or underground explosions buried either in noise or in the surface waves of a larger event.

Discrimination - Earthquakes and Underground Explosions

Studies by Molnar et al. (1969), Savino (1970), and Savino et al. (1971a) showed that discrimination between earthquakes and underground explosions in the western United States recorded at Ogdensburg, on an M_s-m_b basis, is enhanced when M_s is based on the amplitudes of 40 sec (Fig. 1b), rather than 20 sec (Fig. 1a), Rayleigh waves. This same result, although necessarily of a preliminary nature, holds true for western U.S. explosions and earthquakes recorded in Australia ($\Delta \approx 110°$), and for Asian earthquakes and

two presumed Russian explosions recorded at Eilat, Israel. The epicentral distances of these presumed explosions from Eilat are only 18°. As pointed out in the previous section, our detection capability at such small distances is quite good; surface waves from earthquakes of m_b=3.8 or larger are observed. Thus, with future data from Eilat and Chiang Mai we should be able to test for parallelism of the explosion and earthquake populations (Molnar et al., 1969; Savino et al., 1971a) for events of lower magnitudes than possible at Ogdensburg.

Earth Noise.

The spectrum of earth noise between 20 and 130 sec observed in the deep mine at Ogdensburg was shown by Savino (1971) and Savino et al. (1971b) to be characterized by a very stable minimum, or window, between 30 and 40 sec. At longer periods the spectrum increases at 12 to 14 db/oct.

The high-gain instruments are designed as optimum filters for the recording of long-period seismic information. That is, the instrument response curves are shaped to resemble as closely as possible the inverse of the mean spectrum of earth noise with peak recording magnifications of 150,000 between 30 and 40 sec.

Using data recorded on the digital data acquisition system, power spectra of background noise were computed for

the five high-gain sites listed in Fig. 2. Prior to the spectral computations, both the photographic recordings and computer-oscilloscope play-outs of the digital data for each station were analyzed and determined to be free of obvious earthquakes of transients.

The spectra in Fig. 2, which are not corrected for instrument response, indicate that at all five recording sites in different regions of the world there is a minimum in earth noise between 30 and 40 sec. These spectra are for different recording times and show the presence of primary frequency microseisms at Ogdensburg and Fairbanks for the time periods analyzed. The absolute level of earth noise at these five sites is obviously not dependent solely upon depth of overburden. For instance, the level of Chiang Mai, a surface site, plots lowest while that at Ogdensburg, the deepest site, is higher than Chiang Mai, Eilat, and Charters Towers. It is important to note that horizontal noise levels at Charters Towers, Eilat, and the surface site at Chiang Mai are not appreciably higher than the vertical noise levels. Thus we are able to record the horizontals at gains comparable to the verticals. A more detailed investigation into the spectral structure and temporal behavior of earth noise at these five sites is under way and will be reported on in the future.

Of special interest is the temporal variation in the horizontal noise level at Fairbanks. To date we have found that the background noise level recorded on the horizontal components can undergo order of magnitude variations in amplitude. This noise is long-period (T>50 to 60 sec) and does not appear on the vertical component. A special investigation into this noise is under way.

Mantle Love and Rayleigh Waves

A study of mantle Love and Rayleigh waves with periods longer than 50 to 60 sec, excited by earthquakes in various seismic regions, was initiated. The objectives of this study are to investigate the dependence of the excitation of these waves on the focal depth, magnitude and location of seismic events. In addition, the multiplicity of recording sites allows an excellent opportunity to investigate the Q structure of the upper mantle for many different regions.

Figure 3 shows the epicenters of various earthquakes that generated G and inversely dispersed Rayleigh waves as observed at Charters Towers (CTA). These data only cover a two month time period. G waves from 36 events have been observed and cataloged. The smallest event from which G_1 was observed occurred off the west coast of Columbia ($\sim$135°) with a reported (USCGS) magnitude m_b of 4.8. The horizontal component seismogram (NLO) in Fig. 3 shows multiple G phases

(G_1 to G_4) excited by the San Fernando earthquake of 9 February 1971. A group velocity of 4.5 km/sec was computed for these waves over the oceanic path.

The inversely dispersed Rayleigh waves with periods between 40 and 200 sec in Fig. 3 are typical of those recorded from many small events at different azimuths.

At the present time all events that are observed to excite mantle waves are being catalogued. These data will then be subjected to more sophisticated analysis techniques.

Free Oscillations

An investigation of the modal structure and Q values for free oscillations excited by shallow and deep focus earthquakes was started. The digital data allows for accurate spectral calculations using computer programs described in section V.

Fundamental spheriodal modes between ${}_0S_2$ (3206 sec) to ${}_0S_{34}$ (236.5 sec) were observed after the west New Guinea earthquake of 10 Jan 1971. This event occurred at 07h17m03.7s and was assigned an m_b of 7.3 (USCGS, PDE). Approximately 24 hours of digital data from Ogdensburg were used in the spectral calculations.

In the future we plan to separate spheroidal and torsional modes of oscillation using vertical and horizontal data from all the high-gain stations. For those stations that are not favorably located azimuthally, rotation of the

station coordinate system using the N/S and E/W data will aid in separating the various modes. In addition, data from all the stations will allow us to measure phase velocities for many different paths.

TABLE 2

Rayleigh Wave Detection Thresholds for 3 High-Gain Stations

Number of Events Recorded Over 230 Hours

PDE	Ogdensburg Charters Towers and Fairbanks	Unreported Events	Reported (USCGS) But Not Observed on High-Gain Records
117	198	93	12

Unreported Events Per Station

Ogdensburg	39
Charters Towers	56
Fairbanks	30
*Total	125

*While the number of separate unreported events is 93, some of these events were observed at one or more stations thereby increasing the total number of unreported events.

TABLE 3

World-Wide Detection Thresholds in Terms of m_b

Using 3 Station Network Ogdensburg, Charters Towers, & Fairbanks
(OGD) (CTA)

Location	*Threshold (m_b)	Nearest Station	Δ of Near Station
Central Alaska	3.8	Fairbanks	5
Gulf of Alaska	3.9	Fairbanks	7
Alaskan Peninsula	3.9	Fairbanks	10
Andreanof Island	4.1	Fairbanks	20
Rat Island	4.1	Fairbanks	22
Hokkaido, Honshu	4.4	Fairbanks	45
Kurile, Kamchatka	4.3	Fairbanks	35
New Guinea, Solomon Island	3.8	CTA	15-20
New Hebrides	3.8	CTA	18
Western Indian Ocean	4.4	CTA	70
Easter Islands	4.5	CTA	85
South Sandwich	4.7	CTA	100
Turkey, Greece, Balkans	4.3	OGD	80
Chile	4.5	OGD	75
Peru	4.4	OGD	50
Colombia	3.9	OGD	35

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* The smallest value of m_b reported by USCGS, PDE for which surface waves are observed.

Location	*Threshold (m_b)	Nearest Station	Δ of Near Station
Galapagos	4.0	OGD	43
Central America, Mexico	3.9	OGD	30
Gulf of California	3.9	OGD	35
Southern California	4.3	OGD	35
Northern California	4.4	OGD	35
Nevada, Utah	4.4	OGD	30
Central Atlantic	3.9	OGD	30
Iceland	4.0	OGD	38
Arctic Ocean	4.2	OGD	45

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Res., 76, in preparation, 1971b.

*Papers published under this contract.

FIGURE CAPTIONS

Figure 1 a and b. Events in the western United States recorded at Ogdensburg. Comparison of peak-peak amplitudes (a) 20-sec Rayleigh waves, and (b) 40-60 sec Rayleigh waves as a function of m_b as determined by Evernden's formulas (1967). The closed circles denote earthquakes in the Gulf of California; closed triangles depict earthquakes in the northwestern United States; +'s depict aftershocks of NTS explosions; x's denote 29 Palms (California) earthquakes; the closed squares represent earthquakes in Idaho. The open circles represent explosions at NTS, the open square denotes Rulison which occurred at Rifle, Colorado. The circles (closed and open) with arrows denote events not observed. These points are plotted at the noise levels at those times. Note that earthquake lc and explosion populations separate better on a M_s 40-60 basis (Fig. 1b) than on a M_s 20 sec basis (1a).

Figure 2. Noise spectra based on five hours of vertical component data from each site recorded digitally. These spectra are plotted at the absolute level of ground motion at 40 sec but are not corrected for instrument response.

Figure 3. Map of world centered on Charters Towers, Australia, showing location of epicenters for those events which excited mantle Love and Rayleigh waves.

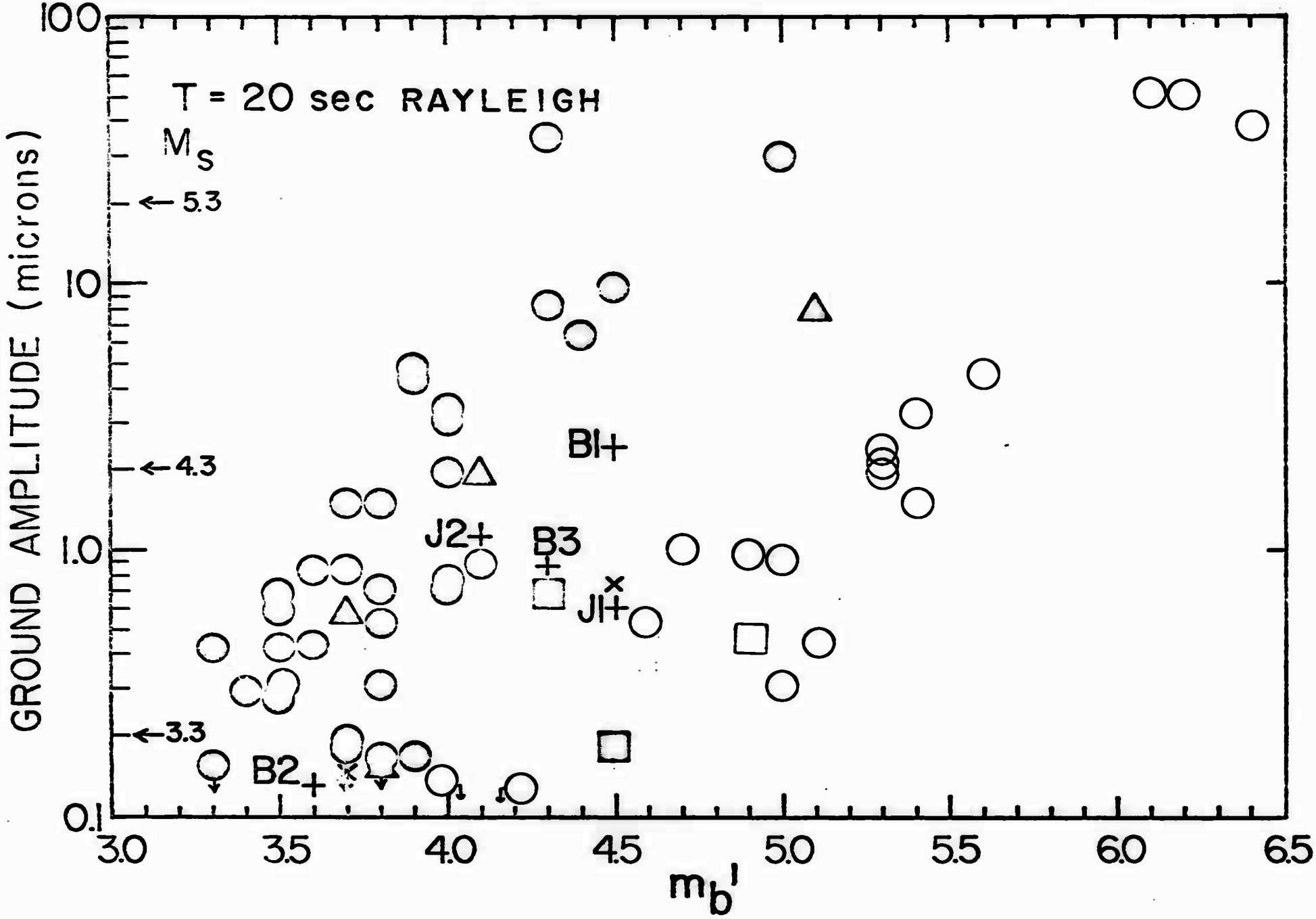
T = 20 sec RAYLEIGH
M_S
← 5.3
← 4.3
← 3.3
B1
J2
B3
J1
B2
GROUND AMPLITUDE (microns)
100
10
1.0
0.1
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
m_b'

Figure 1a

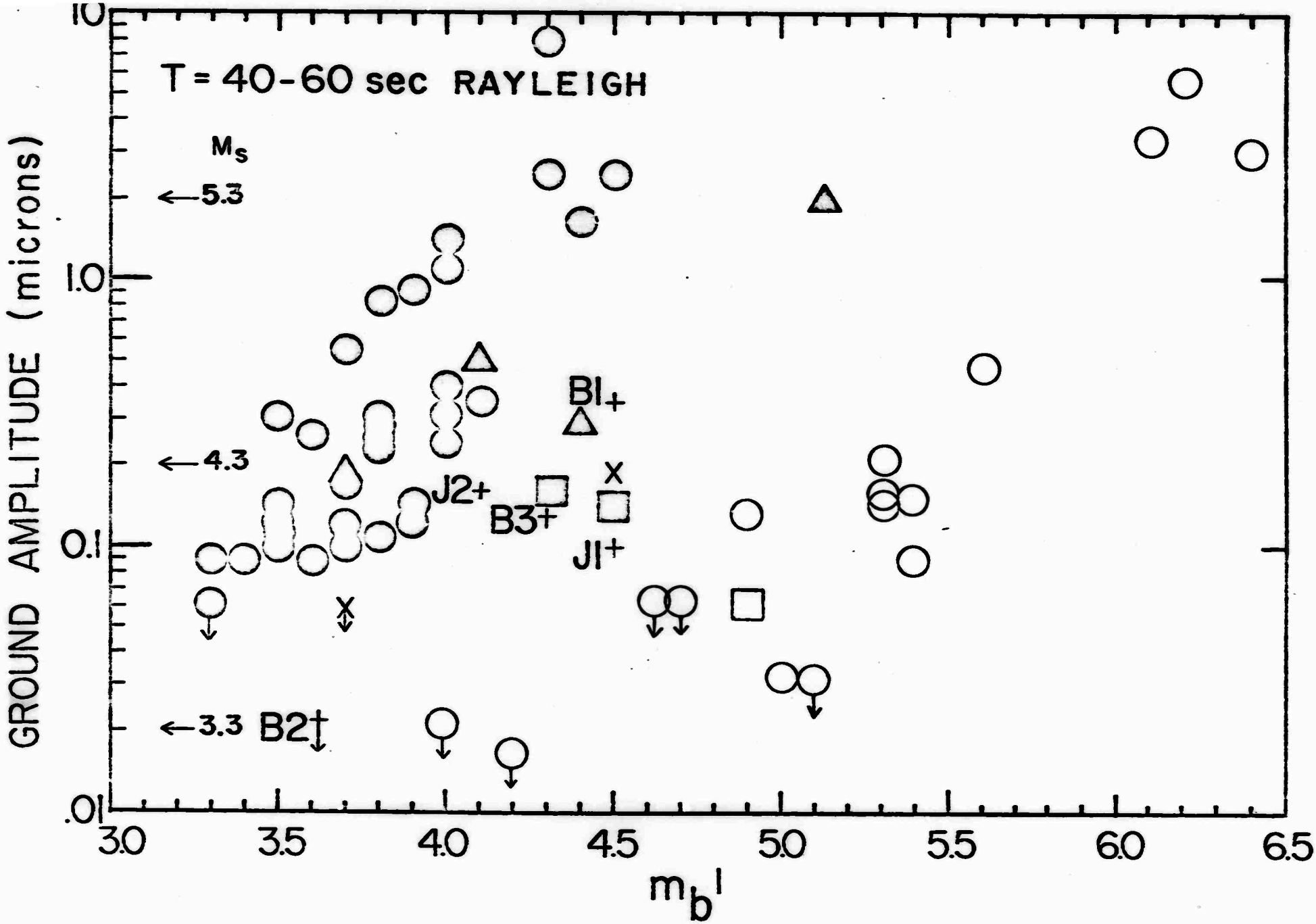
T = 40-60 sec RAYLEIGH
M_s
←5.3
←4.3
←3.3
B1+
J2+
B3+
J1+
B2
GROUND AMPLITUDE (microns)
10
1.0
0.1
.01
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
m_b'

Figure 1b

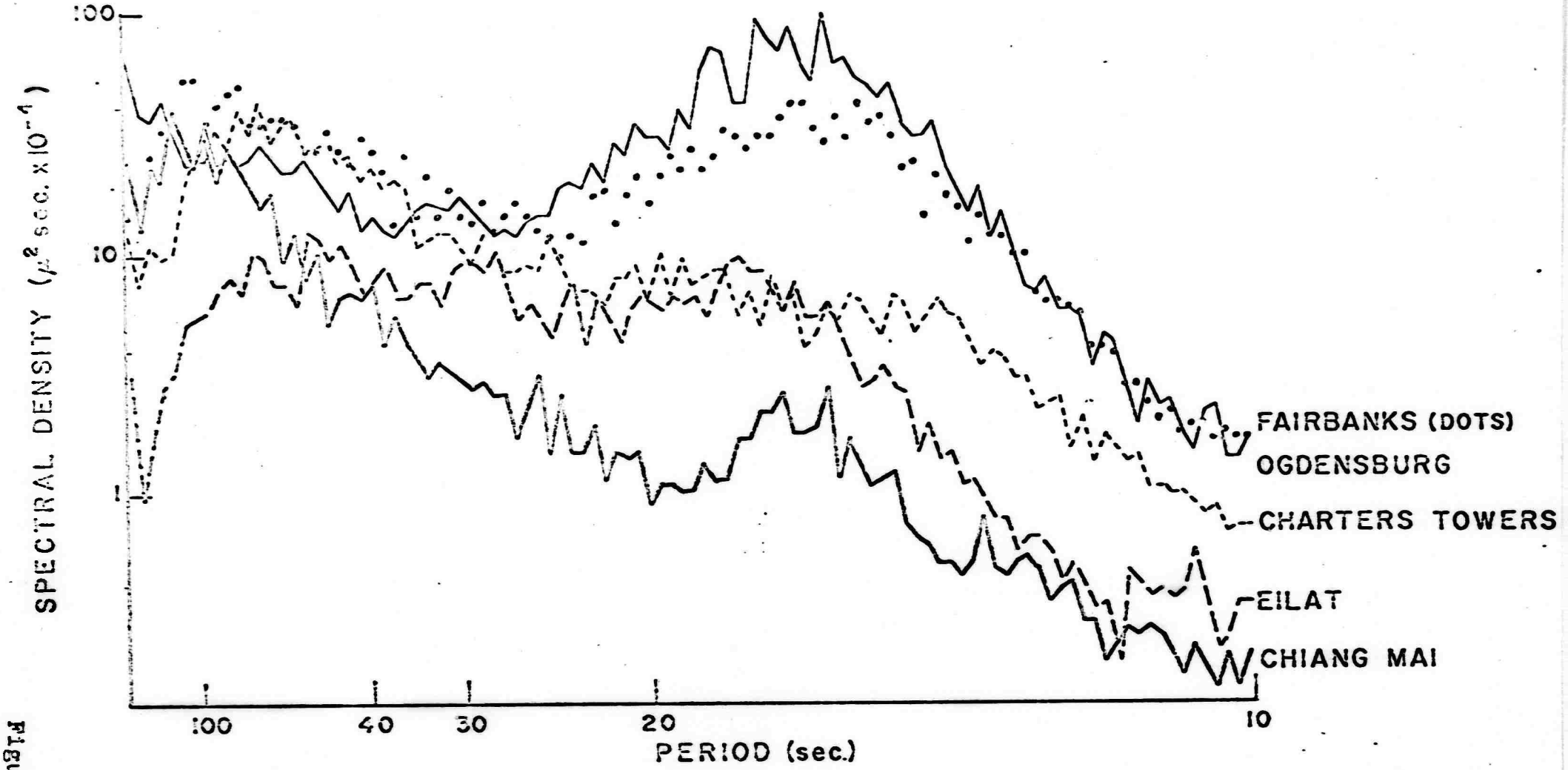
SPECTRAL DENSITY (μ^2 sec. x 10^{-4})
100
10
1
100
40
30
20
10
PERIOD (sec.)
FAIRBANKS (DOTS)
OGDENSBURG
CHARTERS TOWERS
EILAT
CHIANG MAI

Figure 2

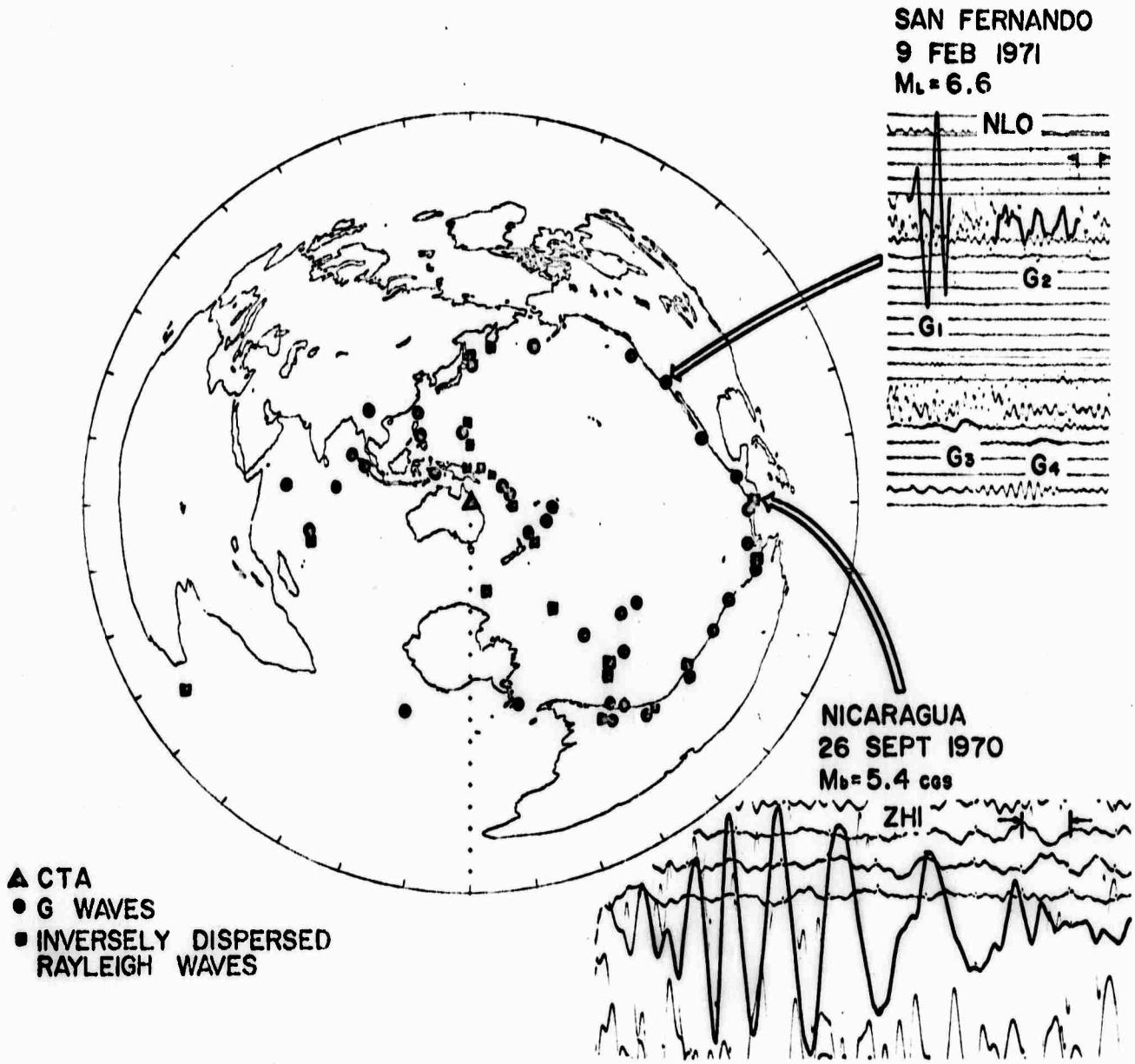
SAN FERNANDO
9 FEB 1971
M_L = 6.6
NLO
G2
G1
G3
G4
NICARAGUA
26 SEPT 1970
M_b = 5.4 cos
ZHI
CTA
G WAVES
INVERSELY DISPERSED RAYLEIGH WAVES

Figure 3