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LONG-PERIOD SEISMOLOGICAL RESEARCH PROGRAM

Lynn R. Sykes, et al

Lamont-Doherty Geological Observatory

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13. ABSTRACT

Approximate detection thresholds of the VLP stations for long-period surface waves were determined. Based on a special listing of events for a one month time period, 90% of the reported shallow ($h \leq 50km$) earthquakes down to $m_b=4.2$ were detected on the basis of either Rayleigh or Love waves for epicentral distances as great as 30°. For as many as 10% of the events that we observed, the detections were based on the observance of Love waves only. To date our results indicate that the VLP station EIL is the most effective station for discrimination between earthquakes and presumed explosions in central Asia. Signal enhancement techniques employing the VLP digital data appear to be able to lower the thresholds based on visual analysis of the seismograms by 0.2 to 0.3 m_b units.

One of the most significant results of our research on long-period earth noise ($T \geq 20sec$) is that all the VLP stations are limited by ground motion at these longer periods. In particular, for periods between 30 and 50 sec the level of this ground motion is 15 to 20 dB above system noise and recognition of the source could lead to techniques that would affect a dramatic improvement in the signal-to-noise ratio of the VLP stations. Additional results on earth noise are based on observations at OGD on the decay rate with depth of the horizontal-component of earth noise. The observations indicate that the effects of wind noise and atmospheric turbulence are greatly attenuated in competent rock at depths of 150 to 200 m.

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SUMMARY

During the past year our research effort concentrated on the detection and discrimination capabilities of the VLP stations and the development of techniques to enhance these capabilities. Approximate detection thresholds of the VLP stations for long-period surface waves were determined. Based on a special listing of events for a one month time period, 90% of the reported shallow ($h \leq 50km$) earthquakes down to $m_b=4.2$ were detected on the basis of either Rayleigh or Love waves for epicentral distances as great as 30°. For as many as 10% of the events that we observed, the detections were based on the observance of Love waves only. The improved detection of Love waves, as well as Rayleigh waves, may offer a solution to the anomalous event problem: earthquakes occurring in certain regions (e.g. central Asia) that mix with the explosion population on an M_s-m_b diagram. As the M_s values for these anomalous events are customarily determined using the amplitudes of Rayleigh waves, the problem may well be just with the excitation of Rayleigh waves by these earthquakes, and the consideration of Love waves in terms of M_s(Love)-m_b, radiation pattern, and the ratio of Love to Rayleigh might provide for discrimination.

To date our results indicated that the VLP station EIL is the most effective station for discrimination between earthquakes and presumed explosions in central Asia. Based on visual analysis of EIL seismograms, the earthquake and presumed explosion populations are well separated down to earthquakes of magnitude $m_b=4.5$. Signal enhancement techniques employing the VLP digital data appear to be able to lower the thresholds based on visual analysis of the seismograms by 0.2 to 0.3 m_b units.

SUMMARY (cont.)

One of the most significant results of our research on long-period earth noise ($T \geq 20$ sec) is that all the VLP stations are limited by ground motion at these longer periods. In particular for periods between 30 and 50 sec, the level of this ground motion is 15 to 20 dB above system noise and recognition of the source could lead to techniques that would affect a dramatic improvement in the signal-to-noise ratio of the VLP stations. Additional results on earth noise are based on observations at OGD on the decay rate with depth of the horizontal-component of earth noise. The observations indicate that the effects of wind noise and atmospheric turbulence are greatly attenuated in competent rock at depths of 150 to 200m.

The VLP data are proving to be especially important for many different seismological studies including focal mechanisms for small magnitude events, the occurence of earthquake swarms, and source and propagation path effects on long-period body and surface waves.

INTRODUCTION

During the past twelve months of the subject contract, the purposes of the research program were:

1. To maintain the six VLP stations previously installed by Lamont while affecting an orderly transition of maintenance responsibilities for those stations to the NOAA group at Albuquerque, New Mexico. During the last two weeks in April personnel from Lamont closed out the station at Fairbanks, Alaska, and shipped all the equipment to Albuquerque.

2. To conduct seismological research on the long-period analog and digital data from the VLP stations.

Analysis of the analog and digital data has been conducted on the following topics:

1. Discrimination between earthquakes and presumed explosions in central Asia.

2. The determination of detection thresholds for long-period seismic waves from earthquakes and underground explosions.

3. Various techniques for enhancing the signal to noise ratio (S/N) of seismic waves from small magnitude events recorded digitally.

4. Investigation of the behavior and sources of earth noise at periods longer than 20 seconds.

5. Various seismological investigations including the study of dc tilts associated with large ($M_s \geq 7.5$) earthquakes and background secular tilts observed on the displacement outputs at the VLP stations; surface wave spectra for swarm-type earthquakes; focal mechanism studies.

The most significant result of the data analysis pertinent to the earthquake - explosion discrimination problem is based on the study of surface wave detection thresholds and earth noise at periods longer than 20 seconds. Inclusion of data from the stations at Eilat, Israel (EIL), and Kongsberg, Norway (KON) show that long-period surface waves are often observed from many shallow earthquakes located in central Asia with magnitudes as low as $m_b=4.1$. These relatively low threshold values can sometimes be lowered by 0.2 to 0.3 m_b units by means of digital filtering techniques (polarization and azimuthal) thereby extending the applicability of the M_s-m_b discriminant to smaller magnitude events. System noise levels between 30 and 50 sec are at least 15 dB below earth noise levels in the same period range. Thus recognition of the source of this earth noise, its effective wavelength, and temporal and geographical behavior could possibly result in a dramatic improvement in the detection capabilities of the VLP stations.

I. STATION MAINTENANCE

During the first three months of the subject contract, considerable time was spent preparing for and carrying out combined inspection - maintenance trips to the VLP stations at Charters Towers, Australia (CTA); Chiang Mai, Thailand (CHG); Kipapa, Hawaii (KIP); and Matsushiro, Japan (MAT). As a result of these trips, several recommendations were made for improvements such as; the addition of air-conditioners in the recording rooms at CTA and CHG for more efficient operation of the digital recorders, and instrument repair techniques that should result in greater continuity of the analog data. In addition, personnel at each site were thoroughly advised of the transition of maintenance responsibilities from Lamont to NOAA.

During the last two weeks in April 1972, a two man team from Lamont traveled to Fairbanks, Alaska, to close out the station FBK. All the equipment at that site, including the instrument tanks, were crated and shipped either by truck or airplane to NOAA at Albuquerque. The final recordings from FBK are dated 25 April 1972.

II. DATA

Seismograms and magnetic tapes from all the VLP stations were sent to Lamont up to 1 September 1972 for quality control. As explained in previous reports, the magnetic tape data were examined on a playback system (cathode ray tube) and compared with the seismograms. The NOAA group at Albuquerque was advised of any malfunctions detected. After examining the tapes for quality control the tapes were copied and the originals forwarded to Texas Instruments. The seismograms are sent to VELA Seismological Center before being film chipped in Asheville, North Carolina. Since 1 Sept. the NOAA group at Albuquerque has been copying tapes and sending the original tapes and seismograms directly from Albuquerque to the VELA Seismologcial Center. At the present time there is no back-log of seismograms from any of the stations at Lamont.

III. RESULTS OF THE DATA ANALYSIS

A. <u>Long-period discriminants between explosions and earthquakes</u>: One of the most effective teleseismic discriminants between earthquakes and underground explosions is that based on a comparison of long-period surface wave magnitudes (M_s) and short-period body wave magnitudes (m_b) for these two types of events. Previous results on the M_s-m_b discriminant, which were based on data from the original VLP seismograph system at Ogdensburg, New Jersey (OGD), were reported by Molnar et al. (1969), Evernden et al. (1971), and Savino et al. (1971). Their results suggested that the effectiveness of the M_s-m_b discriminant is probably as great as m_b=4 as at m_b=5 for earthquakes and underground explosions occuring in several different regions of the world. A further important result of these investigations was that Love waves with periods of 20 and 40 sec could also be used as a discriminant on an M_s(Love)-m_b basis.

In a more recent study, Savino et al. (1972a) presented results on discrimination between earthquakes in the Kirzig-Sinkiang-Tadzhik-Tibet region and presumed Russian explosions. Their results were based on long-period surface wave data recorded at Eilat, Israel (EIL). This station is approximately 30° from presumed Russian explosions and exhibits a better detection threshold for surface waves from these presumed explosions and earthquakes in the same general region than the VLP stations at Chiang Mai, Thailand (CHG); Kongsberg, Norway (KON); and Toledo, Spain (TLO).

In Figure 1, peak-to-peak amplitudes of Rayleigh waves with periods near 20 sec (left-hand plot) and 40 sec (right-hand plot) recorded at EIL from earthquakes in the Kirzig-Sinkiang-Tadzhik-Tibet region (closed circles) and presumed Russian explosions (open circles) are plotted as a function of m_b (NOAA). The ordinate on the 20 sec plot describes the M_s scale for these events as indicated by the numbers and arrows. Although the data are limited there are two rather important points about Figure 1.

Firstly, the earthquake and explosions populations are completely separated even though the M_s determinations are restricted to measurements from a single station. Secondly, the two populations do not show any sign of convergence at the low magnitudes. This latter result is similar to that found at OGD for earthquakes and explosions in the western United States, the Aleutians, and the Novaya Zemlya region by Evernden et al. (1971), and Savino et al. (1971).

One of the problems with the investigation of events in central Asia, with magnitudes between 4.0 and 4.5, is that the NOAA listings (PDE) are not complete in the magnitude range. By utilizing reports from the large arrays (LASA, NORSAR, ALPA) in conjunction with the PDE, a more complete data set will be available for study and we will be able to better investigate the behavior of the earthquake and explosions populations at small magnitudes.

While the detection threshold for surface waves from the presumed explosions plotted in Figure 1 is rather high, about m_b 5.5 or M_s 3.2, it is important to note that these results are based on visual analysis of seismograms only. Methods of signal enhancement employing digital filtering techniques to be described in a later section should improve the threshold value at EIL and the other VLP stations and allow us to test for separation and parallelism of the earthquake and explosion populations to small magnitudes for events in central Asia.

As pointed out in several publications (Molnar et al., 1969; Savino et al., 1972a) Love waves are often recorded on VLP seismograms even when Rayleigh waves are not observed from events in many different regions of the world. This is particularly significant since the effectiveness of several discriminants (radiation pattern, M_s(Love)-m_b, ratio of Love to Rayleigh) based on the recording of either Rayleigh and/or Love waves appears most promising. In addition, a possible explanation of the anomalous behavior (M_s(Rayleigh)-m_b wise) of certain Eurasian events is that these events may be deeper than normal (40 to 100 km) and characterized by strike-slip mechanisms. If this is so then we would expect poor excitation of Rayleigh waves for periods from 10 to 100 sec and thus more explosion like M_s-m_b values. However, if this hypothesis is correct then these events should excite large Love waves and thus could be discriminated on an M_s(Love) - m_b basis or perhaps on a ratio of Love to Rayleigh wave excitation basis.

B. <u>Detection thresholds for small magnitude events</u>:

With the advent of short-period arrays and the resulting improvement in the detection capabilities for short-period body phases (m_b), the principal limitation to the application of the M_s-m_b discriminant to small magnitude (m_b<4.5) events is determined by our recording capabilities of long-period surface waves. Thus it is of prime importance to determine the capabilities of the newly installed VLP stations for recording long-period surface waves from small magnitude events and thereby recognize and develop techniques that will improve these capabilities.

Recently the group at Linclon Laboratory generated a special listing of events for the time period 20 Feb 1972 through 19 Mar 1972. This time period is referred to as the International Seismic

Month (ISM). More than 1200 events were definitely identified on the basis of short-period recordings from the various arrays (LASA,NORSAR,ALPA), the Canadian stations, and the WWNSS stations. This listing represents a considerable improvement over the Preliminary Determination of Epicenters (PDE) listing of NOAA, especially for small magnitude (m_b<5.0) events, and provides an excellent data base for the determination of approximate detection thresholds of the existing VLP stations.

To date seismograms from several of the VLP stations have been analyzed for all the shallow (h ≤ 50km) events reported in the ISM listing. Preliminary results for Kongsberg, Norway (KON), and Eilat, Israel (EIL) are shown in Figures 2a and 2b, respectively. The solid circles designate those events observed, the x's events not observed. The magnitude of an event is given along the abscissa. The event symbolized by the square in these two figures is a presumed Kazakh explosion, observed at EIL but not at KON.

There are a number of interesting observations based on the results in Figures 2a and 2b;

1) The 90% detection threshold is approximately m_b=4.2 at epicentral distances of 30° from both stations.

2) Approximately 10% of the observed events were based on Love waves only.

3) Surface waves with periods between 30 and 50 sec were observed more often than those with periods between 15 and 25 seconds.

4) The threshold values, which were based on visual analysis of seismograms, can probably be lowered by 0.2 to 0.3

m_b units by more sophisticated signal enhancement techniques possible with the digital data recorded at the VLP stations.

It should be noted that this kind of analysis, in addition to yielding detection capabilities, serves to point out any weakness in the coverage of the existing VLP stations for events occurring in different regions of the world and should provide important information on the location of future improved long-period stations.

C. Signal enhancement techniques:

Of all the signal-enhancement techniques evaluated, polarization filtering seems to promise the greatest gains in detection and discrimination. By polarization filtering we mean a time-varying filter whose instantaneous transfer function depends on the relative phase spectrum between the vertical and horizontal ground motion. In this way, seismograms can be filtered to suppress motion which is not rectilinearly polarized (that is, filtered to pass only body waves) or they can be filtered to suppress all but quadrature polarization (which passes only Rayleigh waves). Filtering seismograms both ways gives a clean separation of the body wave arrivals and their accompanying PL leaking mode phases.

The success of this filter depends on the polarization of the noise. At periods less than 30 seconds the noise is predominantly Rayleigh wave type polarity and a body wave filter gives excellent signal enhancement. At longer periods there is a preliminary indication that the noise is rectilinearly polarized, on a short term basis at least. This need not contradict previous results showing low coherence between vertical and horizontal noise since short runs of the noise may be polarized in-phase followed by other runs of the 180^{o} out-of-phase. In the long run, such noise will have low coherence between the vertical and horizontal. The time-varying nature of the filter adapts itself to the instantaneous polarity of the noise and passes Rayleigh type motion with considerable signal gains. At present, it seems likely that events with detectable Rayleigh waves can be made to give long-period body wave magnitudes by filtering for the PL phases which accompany the body wave arrivals and share their frequency and amplitude characteristics.

Polarization filtering prior to matched filtering using Rayleigh waves should further enhance the signal gain. It is likely that the detection thresholds for surface waves from many earthquakes can, in this way, be lowered by as much as 6dB. One of the most important gains will be the identification of long-period body waves that are not recognizable on analog recordings (i.e., events with only a very small surface wave). A more complete description of these filters and of additional results is described in a publication by Choy and McCamy (1973).

D. Long-period earth noise:

An understanding of the temporal and spatial variations of earth noise in the period range 10 to 100 sec will aid us in the attainment of both quiet long-period recording sites and optimum signal to noise conditions. Both of these factors are of prime importance for the optimum recording of surface waves from small magnitude events and, thus, the application of long-period discriminants (e.g., M_s-m_b).

Murphy et al., (1972) investigated the spectral shape and level of background noise in the period range 10 to 100 sec recorded at seven of the VLP stations. The most important results of this study are:

1) There is a pronounced minimum in the vertical component of the earth noise spectrum between approximately 30 and 50 seconds at all of these seven widely separated sites. This noise minimum provides for a very effective window for observing surface waves from small magnitude events.

2) The absolute level of this noise minimum is the same at all seven of these sites to within 10 dB (a factor of nearly 3 in amplitude). Note that the depth of burial of the VLP stations varies from approximately 0m for Chiang Mai, Thailand (CHG), to 543m at Ogdensburg, New Jersey (OGD).

3) The level of the vertical component of noise at periods longer than 30 sec, unlike that for the 16 to 20 sec band of microseisms, exhibits a very small temporal variation.

A further important result of the noise study by Murphy et. al., (1972) is that the shape and absolute level of the horizontal-component noise spectra are nearly identical over the passband 10 to 100 sec with the vertical-component spectra at those VLP sites with appreciable overburden (EIL,200m; KON,300m; OGD,543m). Also in contrast to horizontal noise levels at those stations with appreciably less overburden (100m), the horizontal noise levels at EIL, KON, and OGD (Savino, 1970; Savino et al., 1972b) have not been observed to undergo diurnal or short-term (a few days or less) variations. Based on results from an experiment underway at the mine of the New Jersey Zinc Co. at Ogdensburg, New Jersey, and from a comparison of microbarometric and seismic recordings at CTA, we attribute the diurnal variations of the horizontal-component noise levels to surface tilting induced by atmospherically generated noise.

Seismic recordings from two-component (Z, N/S) sets of instruments installed on several different levels of the mine at OGD are shown in Figure 3. The horizontal-component (N/S) seismograms are displayed on the right-hand side of this figure in order (from top to bottom) of increasing depth; 180, 340, 500, and 1850 feet. The vertical-component recordings are shown on the left-hand side in the same order. There are two important points to be made:

1) The optimum signal-to-noise ratio (S/N) for the vertical-component seismograms (e.g. note the surface wave train recorded on the top trace of each set of seismograms) is achieved at relatively shallow depths. In fact, at the present time we suspect that most of the noise that is obvious on the 180'Z recordings is the result of a leaky instrument tank allowing for direct pressure effects (buoyancy) on that seismometer. As mentioned previously, our results from all the VLP stations indicate that provided the station is located on competent bedrock, depth of burial does not play a very important role in the actual S/N obtained at a site. At OGD this is a result of the very slow decay rate with depth of earth noise at periods longer than about 30 seconds. Our preliminary interpretation of the sources of this noise are long wavelength disturbances in the atmosphere; either gravity waves or acoustic waves. This is one of the present research topics we are working on.

2) The situation for the horizontal-components is quite different. The data shown in Figure 3 are for daylight hours when wind speeds at the surface were approximately 3-6m/sec. As can be seen from the surface wave signatures indicated by the arrows, a substantial increase in S/N is obtained in going from a depth of burial of 180' to 500' (e.g. a factor of about five). Note also that in going from 500' to 1850', the increase in S/N is less than a factor of two. This latter result indicates that the effects of moderate wind noise and atmospheric turbulence are greatly attenuated at this hard rock site at depths of 500' (150m) to 700' (225m). There are a few occasions however, when winds, with speeds in excess of 15m/sec, generate noise that is observable on the 1850' level horizontal-component instruments. This investigation is most important since the levels of earth noise at periods of 30 to 50 sec observed at all the VLP sites are at least 15 to 20 dB above the system noise levels. Thus recognition of the source (or sources) of earth noise could possibly result in substantial improvements in S/N ratios.

E. General Seismological Investigations:

Various investigations employing the VLP analog and digital data are currently under way. These include:

a.) A study of dc tilts associated with large ($M_s \geq 7.5$) earthquakes and background secular tilts observed on the displacement outputs at the VLP stations. To date, dc tilts have been observed at CTA after a large (M_s=8.0) New Guinea shock and at OGD after a M_s=7.6 earthquake is Sitka, Alaska. Additional large earthquakes are being investigated and the observed dc tilts, as well as dc strains, will be compared with theoretical calculations.

b.) First motion determinations and fault plane solutions. The high-magnification data at long-periods are proving to be extremely valuable for the determination of the proximity of a particular station to a nodal plane, and thus the determination of fault plane solutions using long-period body waves.

c.) Study of earthquake swarms. A study of an earthquake swarm that occured in the Gulf of California on 20 March 1972 has been initiated. Swarm-type earthquakes, by their nature, tend to be of relatively small magnitude (e.g., maximum of m_b(NOAA) = 5.4 in the Gulf of California sequence) and to occur on oceanic spreading centers, often far from any land-base seismographs. For instance only 7 events were reported in the Preliminary Determination of Epicenters (PDE) listings of NOAA as occuring in the Gulf of California during the swarm, whereas very characteristic surface waves from 52 events in this swarm were observed on recordings, especially the horizontal components, from the VLP station at Albuquerque, New Mexico. The VLP stations offer a potentially useful tool for studying this important class of events.

d.) Acoustic-gravity waves from an event on 14 October 1970, presumed to be a Chinese atmospheric explosion, were observed on VLP vertical and horizontal component seismograms written at three different locations in the world, Savino and Rynn (1972). Reliable group velocity data for the atmosphere over propagation paths as long as 97° (10, 800km) were obtained for the period range of 30 seconds to 375 seconds. These data are in agreement with theoretical dispersion curves that are based on the COSPAR-model atmosphere with the effect of winds included. Seismic body and surface waves from this atmospheric event were also recorded at the three stations and were used to determine an epicenter. On 14 April 1971, slow speed gravity waves from another pressure disturbance of meteorological origin were observed with periods between 240 seconds and 360 seconds on seismograms at Ogdensburg, New Jersey. The seismic recordings of the acoustic-gravity and the slow apeed gravity waves are attributed to ground motion produced by surface loading and not to direct pressure effects on the instruments. The observed displacements and tilts from both events are in agreement with those predicted by static loading theory. At the Ogdensburg station, the rock layer above the instruments (543 m) acts as a wavelength filter to suppress wind noise of short wavelength and to enhance signals from long wavelength (coherent) disturbances in the atmosphere.

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FIGURE CAPTIONS

Figure 1. M_s-m_b at 20 and 40 sec (Rayleigh waves) for earthquakes in the Kirzig-Sinkiang-Tadzhik-Tibet region (closed circles) and presumed Russian explosions (open circles). All of these measurements were taken from seismograms written at the high-gain station at Eilat, Israel (EIL). Note the pronounced separation of the two populations.

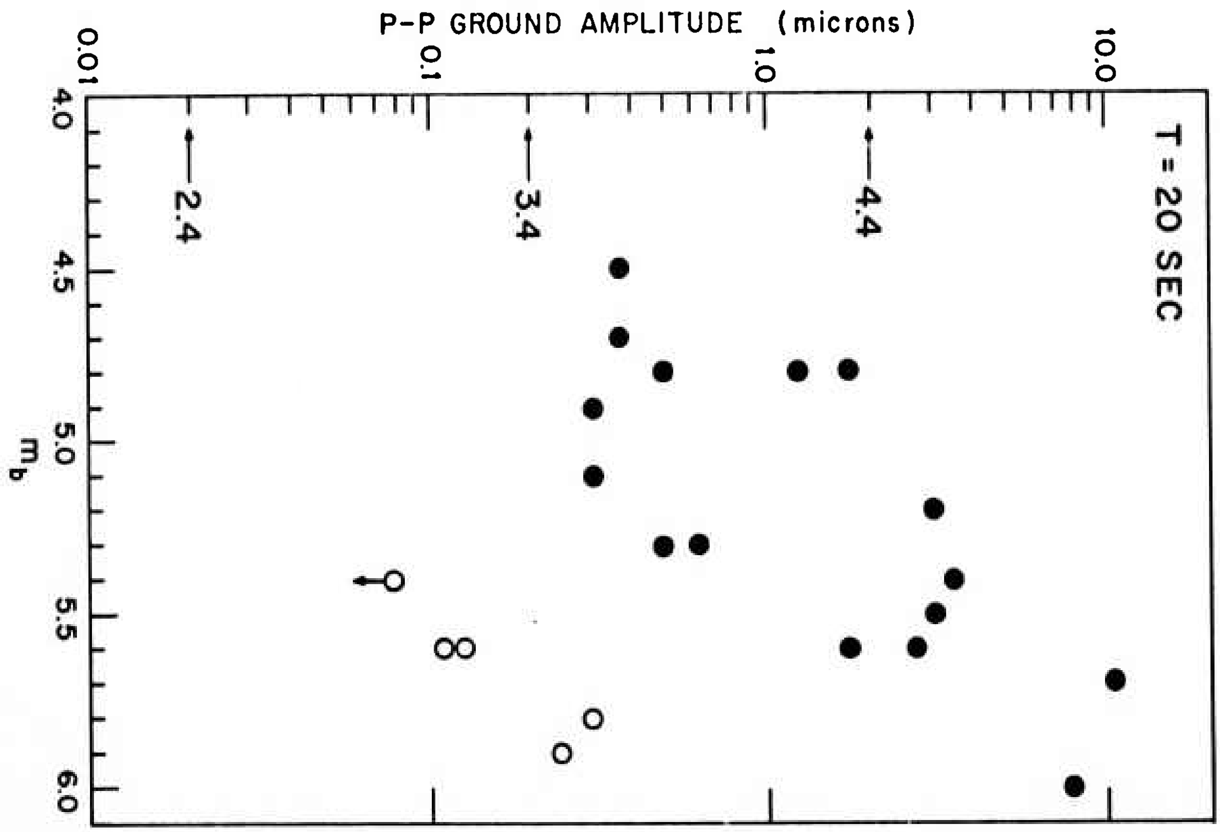
Figure 2a. Detection threshold as a function of epicentral distance for Kongsberg, Norway (KON). The events are those reported in the ISM listing and are limited to shallow focal depths, $h<50$km.

2b. Detection threshold for Eilat, Israel (EIL).

Figure 3. Sets of vertical-component (left-hand side) and horizontal-component (N/S, right-hand side) seismograms from an array of VLP type instrumentation installed on four different levels of the New Jersey Zinc Mine at Ogdensburg, New Jersey. Note the significant increase in S/N for the surface wave train at the tip of the arrows on the N/S seismograms as depth of burial increases. Going from a depth of 500' to 1850' does not significantly reduce the noise background.

Fig. 1

20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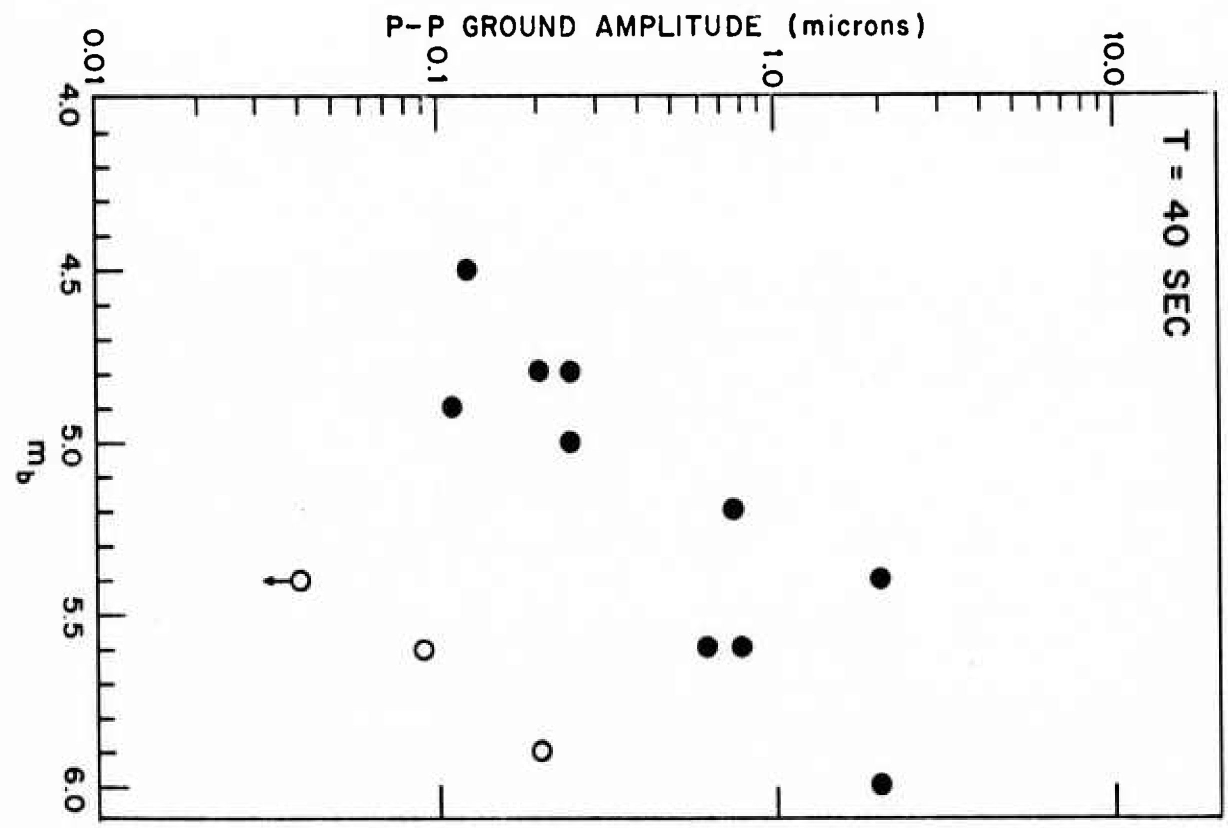
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Fig. 2a

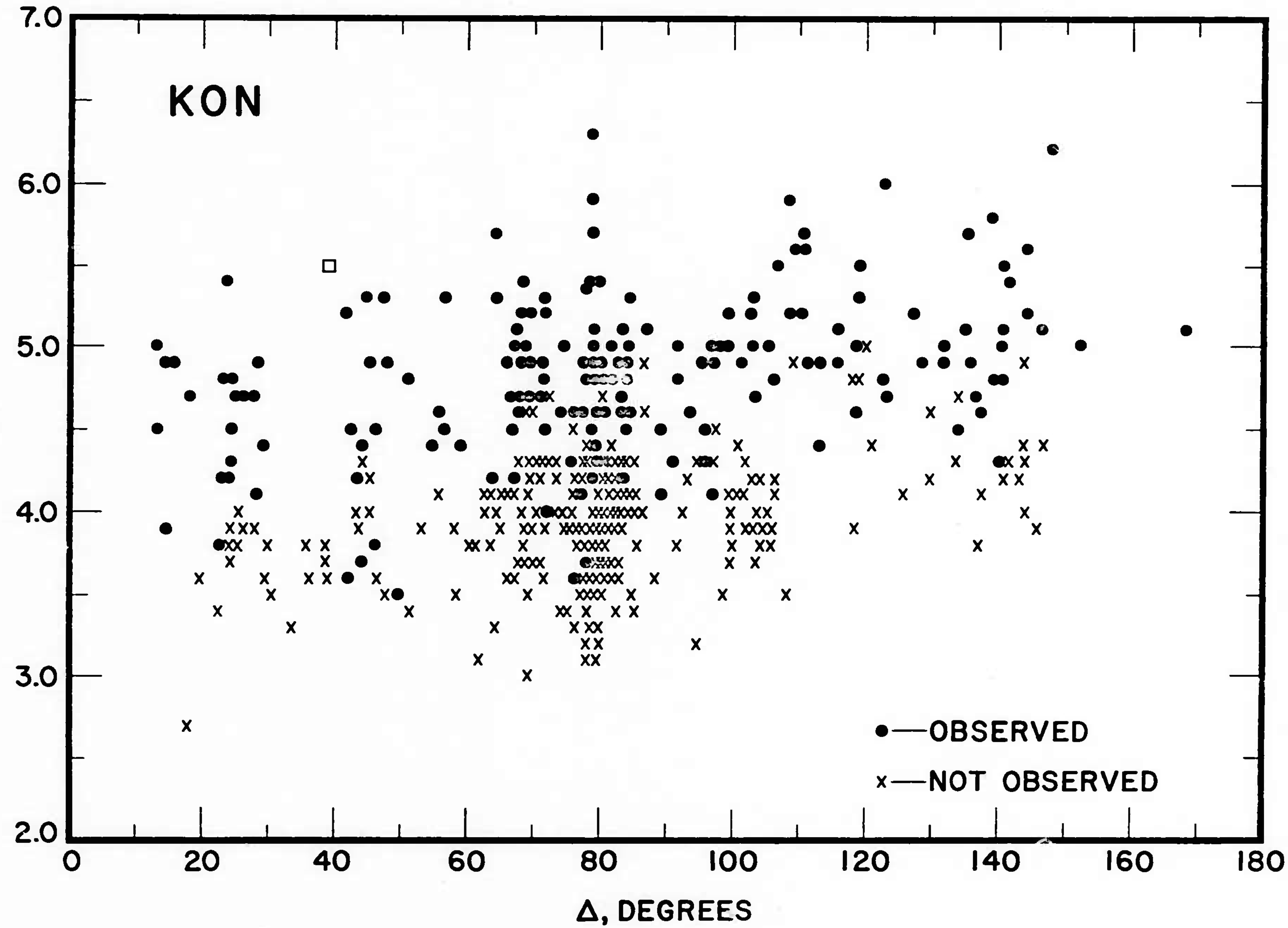
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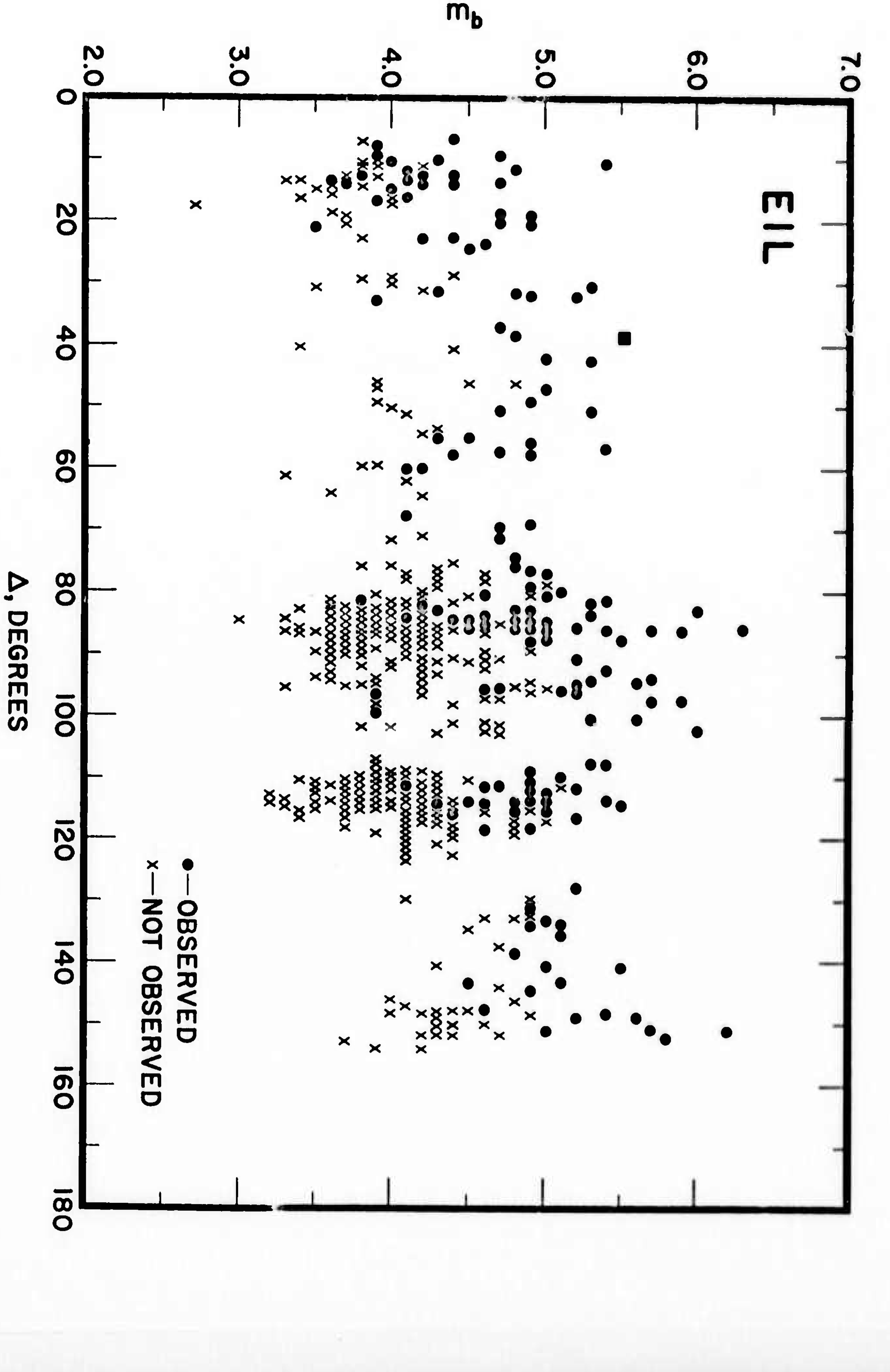
Fig. 2b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m_b
2.0
3.0
4.0
5.0
6.0
7.0
0
20
40
60
80
100
120
140
160
180
Δ, DEGREES
●—OBSERVED
x—NOT OBSERVED

Fig. 3