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TECHNICAL REPORT NO. 65-68

# PERCENTAGES ASSOCIATED WITH THE DETECTION OF LONG-PERIOD SURFACE WAVES FROM LOW-MAGNITUDE EVENTS





THE GEOTECHNICAL CORPORATION
3401 SHILOH ROAD
GARLAND, TEXAS

TECHNICAL REPORT NO. 65-68

# PERCENTAGES ASSOCIATED WITH THE DETECTION OF LONG-PERIOD SURFACE WAVES FROM LOW-MAGNITUDE EVENTS

by

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THE GEOTECHNICAL CORPORATION
3401 Shiloh Road
Garland, Texas



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ILLUSTRATIONS, Continued

ABSTRACT

A statistical survey of LRSM Bulletin data was made to determine the percentage of earthquakes from which long-period surface waves are recorded, as a function of event magnitude. The bases for the percentages were the events located by USC&GS, regardless of depth or epicentral distance. Similar detection-versus-magnitude functions were computed for short-period signals and for long-period surface waves from earthquakes at depths less than 75 km. The long-period seismographs at two LRSM sites, Las Cruces, New Mexico (LC-NM), and La Paz, Bolivia (LZ-BV), are capable of operating at magnifications of 100K. To estimate the capabilities of these sites, a joint distribution of detection percentage versus magnitude and distance was determined for long-period surface waves recorded at LC-NM. For comparison a similar distribution was computed for a typical moderate-gain site, Marysville, California (MV-CL). A survey of the seismological bulletin based on data from the five VELA-UNIFORM observatories (WMSO, CPSO, UBSO, TFSO, and BMSO) determined detection percentage for Rayleigh waves as a function of epicentral distance, magnitude, and magnification of the recording instrument. From this information, functions of detection percentage versus magnitude were computed for instruments operating at 10K, 20K, and 30K. The 50 percent detection levels as functions of distance and magnitude were also calculated for these three magnification levels. From these combined LRSM and Observatory data, it is concluded that the detectibility of long-period surface waves decreases continuously and almost linearly with decreasing magnitude, there being no apparent magnitude threshold below which earthquakes do not generate such waves. Also, the detectibility of surface waves is not highly sensitive to changes in epicentral distance. The greatest percentage increase in surface waves detected resulting from increased magnification is obtained in the lower magnitude ranges.

# PERCENTAGES ASSOCIATED WITH THE DETECTION OF LONG-PERIOD SURFACE WAVES FROM LOW-MAGNITUDE EVENTS

## 1. INTRODUCTION

This report presents and discusses the results of several statistical studies conducted to assess the current potential for recording long-period surface waves from earthquakes. Emphasis is placed on the detection of surface waves from low-magnitude events, with particular attention to the possibility of improving detection by using seismographs operating at a high magnification.

Two bodies of data were involved in the studies - the seismological bulletin based on data from the Long-Range Seismic Measurements (LRSM) mobile stations and the bulletin compiled from the five VELA-UNIFORM observatories

Wichita Mountains Seismological Observatory (WMSO)
Cumberland Plateau Seismological Observatory (CPSO)
Uinta Basin Seismological Observatory (UBSO)
Tonto Forest Seismological Observatory (TFSO)
Blue Mountains Seismological Observatory (BMSO).

These data exist, in reduced form, on digital magnetic tapes. Data for the surveys were compiled by means of a Control Data 160-A Digital Computer.

Because of differences in the recording instruments and analysis philosophies involved, the two bulletins were surveyed separately and in somewhat different manners. The LRSM Bulletin is prepared from the records of ten stations as an aid in determining the extent of the data contained in the records from all forty LRSM teams. Data from the five observatories are analyzed in the greatest possible detail to provide a comprehensive body of information for special studies based on the Observatory Bulletin. The results of the surveys are discussed in separate sections of this report. Section 2 describes the studies of LRSM data and section 4 describes the results obtained from the Observatory bulletins. Section 3 treats data recorded by two exceptionally high magnification, long-period seismographs operated under the LRSM program. Some details of these installations are also reported in this section.

This work was supported by funds authorized under Project VT/4051, Contract AF 33(657)-12145 and Project VT/1124, Contract AF 33(657)-12373. Both projects are under the technical direction of the Air Force Technical Applications Center (AFTAC) and under the overall direction of the Advanced Research Projects Agency (ARPA).

## 2. DATA FROM LRSM BULLETIN NETWORK

### 2.1 GENERAL

Since January 1962, the Long-Range Seismic Measurements Program has operated 40 mobile observatories at more than 200 locations covering the United States and Canada, and at various overseas sites. Each mobile observatory is equipped with a three-component short-period seismograph and a three-component long-period seismograph. Each long-period seismograph includes a Sprengnether Model 201 Vertical Seismometer and two Sprengnether Model 100 Horizontal Seismometers, Geotech Model 5240 Phototube Amplifiers, and bandpass filters. The responses of these seismographs are identical and are shown in figure 1. The seismograph responses peak at a period of about 24 seconds and cut off on both the high- and low-frequency ends at a rate of 18 dB/octave. The output of each seismograph is recorded on both magnetic tape and 35-mm film.

The range of magnifications at which the LRSM long-period seismographs are operated is shown in figure 2. Magnifications, which are measured at a period of 25 seconds, range from less than 5K up to about 70K, with the median at about 15K. The mean is about 20K. These magnifications correspond to normal background trace amplitudes of between 5 and 10 mm.

Since the inception of the program, the 35-mm film recorded by ten of these observatories has been analyzed on a routine basis in preparation of the monthly LRSM Seismological Bulletin. The ten sites whose data are actually read and included in the Bulletin vary from month to month. Figure 3 shows the locations of all the sites from which data have be reported in the Bulletin. They are located principally in the United States, with additional emplacements in Canada, Germany, Norway, and Bolivia.

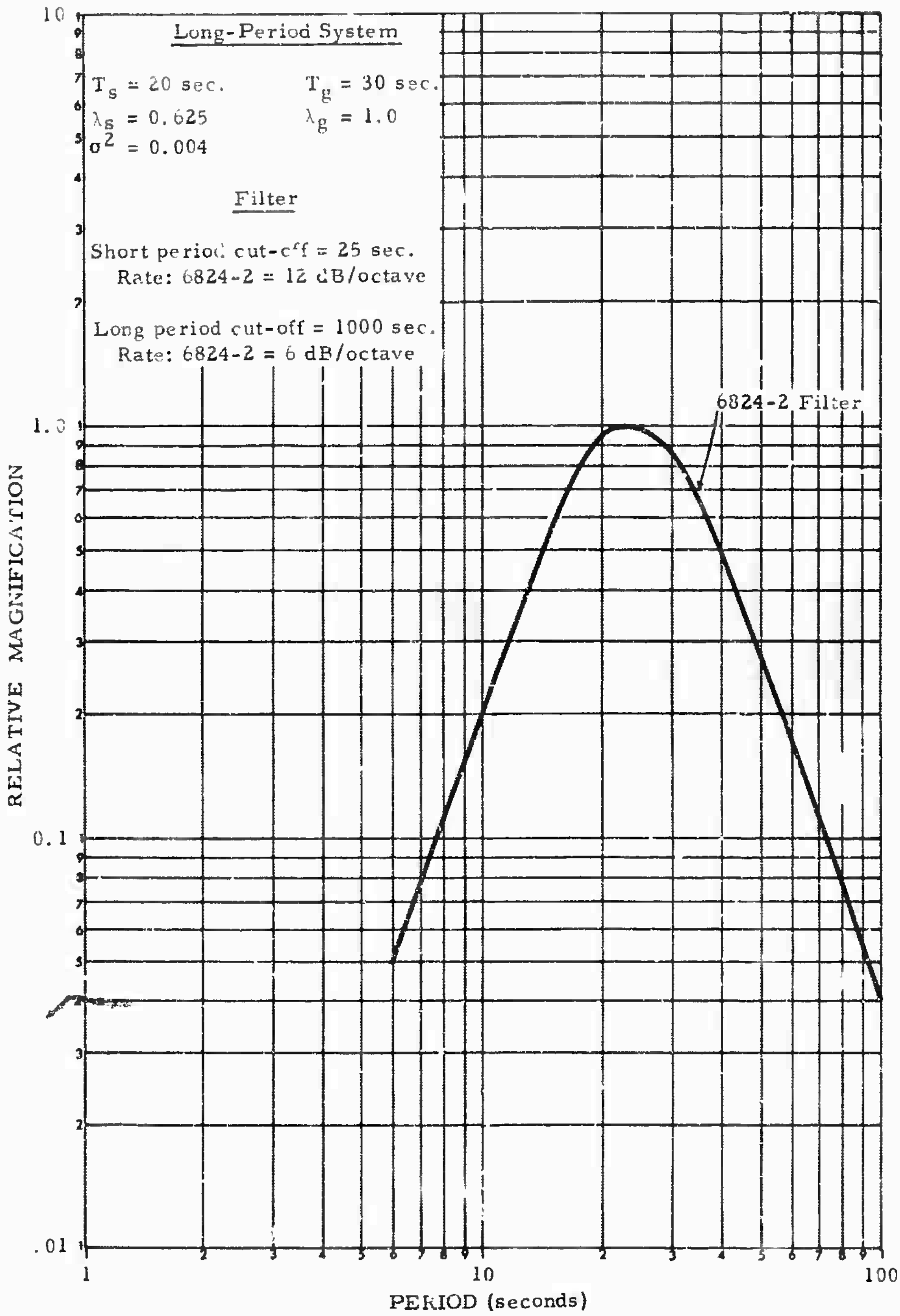


Figure 1. Response of the LRSM long-period seismographs

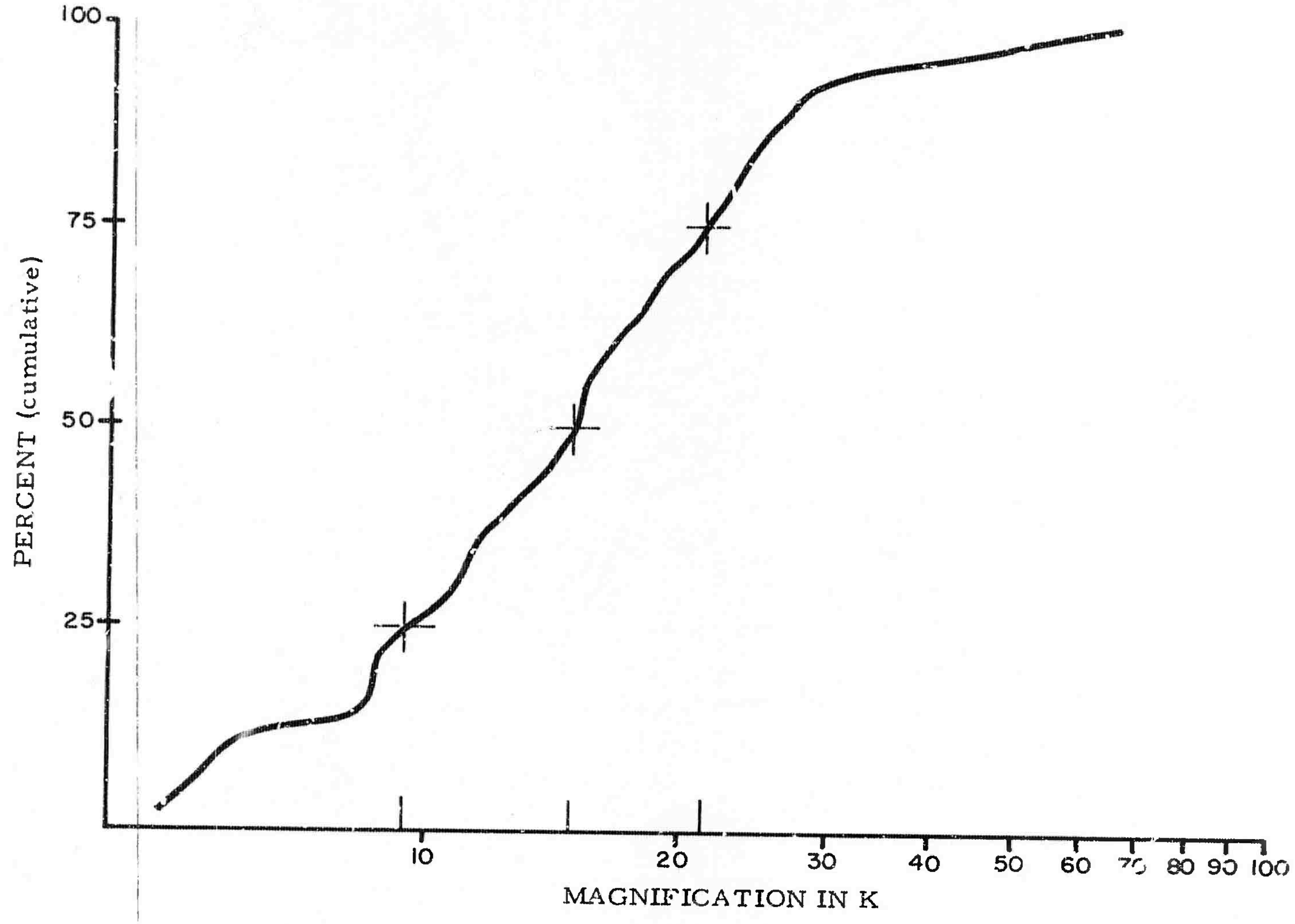


Figure 2. Distribution of magnifications of LRSM long-period seismographs (cumulative)

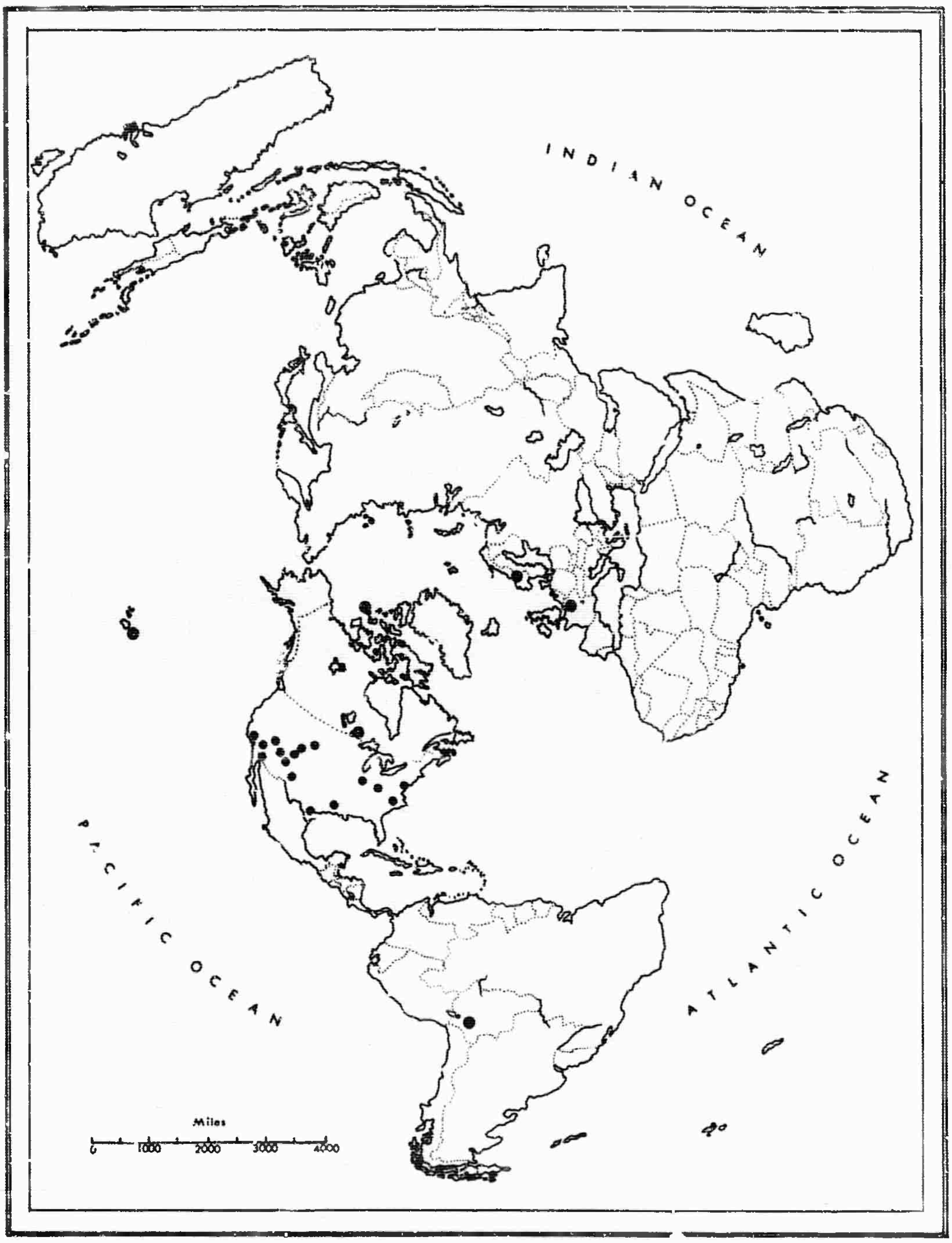


Figure 3. Locations of the LRSM Bulletin Stations
(only ten sites analyzed at any one time)

The data analyzed are associated when possible with epicenters located by the United States Coast and Geodetic Survey (USC&GS); then all information is punched into cards and transferred to digital magnetic tape for computer processing. These digital tapes make it possible to conduct statistical surveys on the data that have been accumulated.

## 2.2 DETECTION OF LONG-PERIOD SURFACE WAVES AS A FUNCTION OF MAGNITUDE

Twenty magnitude categories between 2.0 and 8.0 were defined, and within each category was tabulated the percent of USC&GS-located events from which long-period surface waves (Love, Rayleigh, or unidentified)[1] were detected at any one of the LRSM bulletin sites. The events were assigned to magnitude categories on the basis of the USC&GS magnitudes, with no restrictions applied to focal depth or epicentral distance. From the more than 3 years of data available, a period of 18 months was selected for the survey. The resultant function, which is based on over 6,000 earthquakes, is shown in figure 4. The lowest-magnitude events from which long-period surface waves were detected were in the 3.00 to 3.25 range. However, the total number of events in this category was too few (7) to warrant including it in figure 4.

As expected, the detection percentage increases with increasing magnitude, but it appears to do so in an almost linear manner, an increase in magnitude value of 1.0 generally being accompanied by a 25 percent increase in detectability. Since the linear magnitude scale in figure 4 corresponds to a logarithmic scale in amplitude, one might expect a corresponding logarithmic increase in detectability. However, there are a few irregularities in this detection function, around magnitudes 4.25 and 5.75, which make generalizations difficult.

The detection function for surface waves shown in figure 4 was tabulated with no restriction of focal depth or epicentral distance. In order to determine the

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[1]A previous survey revealed that Love waves are essentially never recorded without corresponding Rayleigh. See Travis, H. S., 1965, Study of surface waves detected by the LRSM long-period systems: The Geotechnical Corporation LRSM Special Projects Group Technical Memorandum, File 151.61 (-12145).

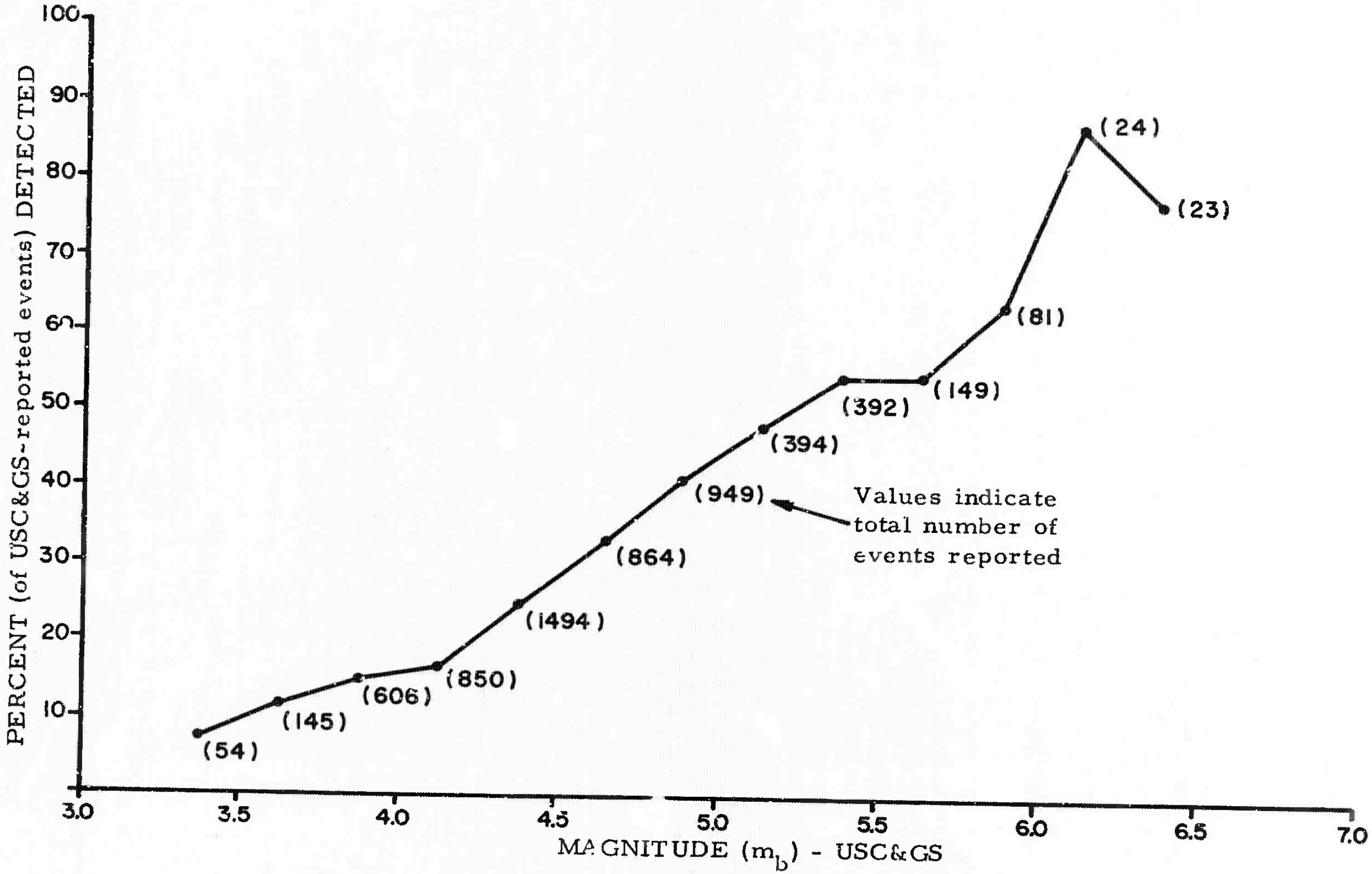


Figure 4. Long-period surface waves detected by the LRSM bulletin network (February, 1963 - July, 1964)

bias introduced by these two variables, the magnitude scale was subdivided into three broad ranges. Frequency distributions of both depth and distance were generated separately for each magnitude range. It should be emphasized that these distributions represent the total number of events reported by the USC&GS, regardless of whether or not they were recorded by the LRSM observatories. The distance tabulated for each event was that to the nearest LRSM Bulletin site.

The depth distributions, which are provided in figure 5, indicate that this factor is essentially independent of magnitude, at least as far as USC&GS data are concerned. The distance distributions are compared in figure 6, and they show that the larger magnitude earthquakes tend to be more distant from the LRSM recordings sites. This may account in part for the failure of the detection percentage function to increase logarithmically with magnitude. It may also be responsible for the seemingly high detection percentages in the region below magnitude 4 (figure 4) because these events were generally closer to the recording sites.

Nevertheless, it is apparent from figure 4 that low-magnitude earthquakes generate long-period surface waves and that the detectability of these waves decreases smoothly and almost linearly with decreasing magnitude down through the lowest-magnitude categories for which data were available. According to these data, there is no apparent magnitude threshold below which earthquakes do not generate long-period surface waves.

Long-period surface waves were recorded from events of magnitude 4.0 or less in many instances. Such recordings were not restricted to any particular distance or region, and in fact, there was at least one instance where surface waves were recorded at a distance of $134^{\circ}$ from an event of magnitude 3.7.

Figure 7 shows how the detection function for long-period surface waves compares with that for short-period phases. Note that the short-period distribution very strongly reflects the same irregularities. Over most of the magnitude range, figure 7 shows that the LRSM Bulletin stations record long-period surface waves from about 25 percent fewer of all USC&GS-reported events than are detected on their short-period systems.

To assess the effect of earthquake depth on the detection function for long-period surface waves, the detection curve was recalculated with the depth restricted to 75 km or less. This reduced the total number of earthquakes involved to about 4800. Both the restricted and unrestricted functions are

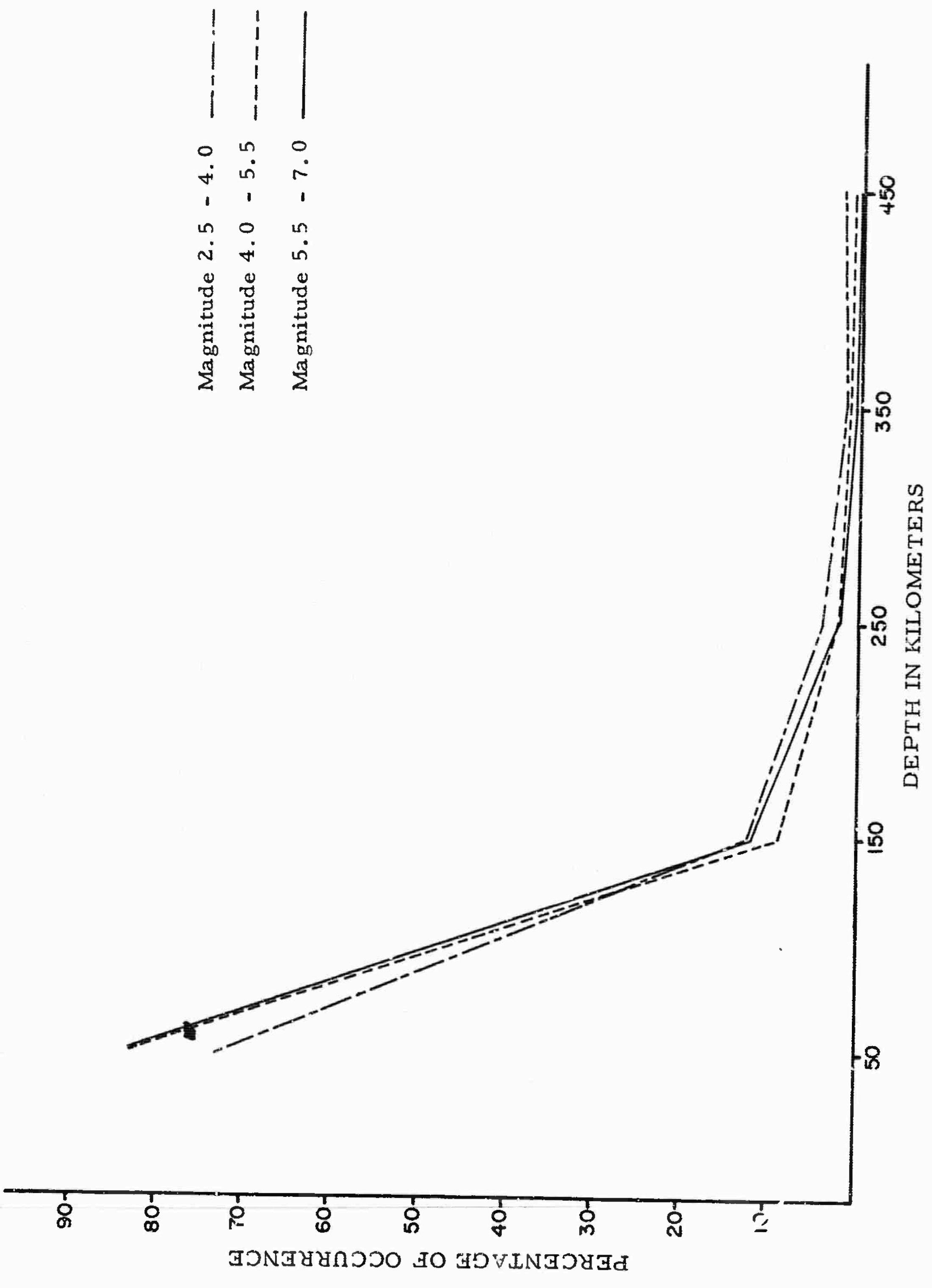


Figure 5. Frequency distributions of earthquake depths

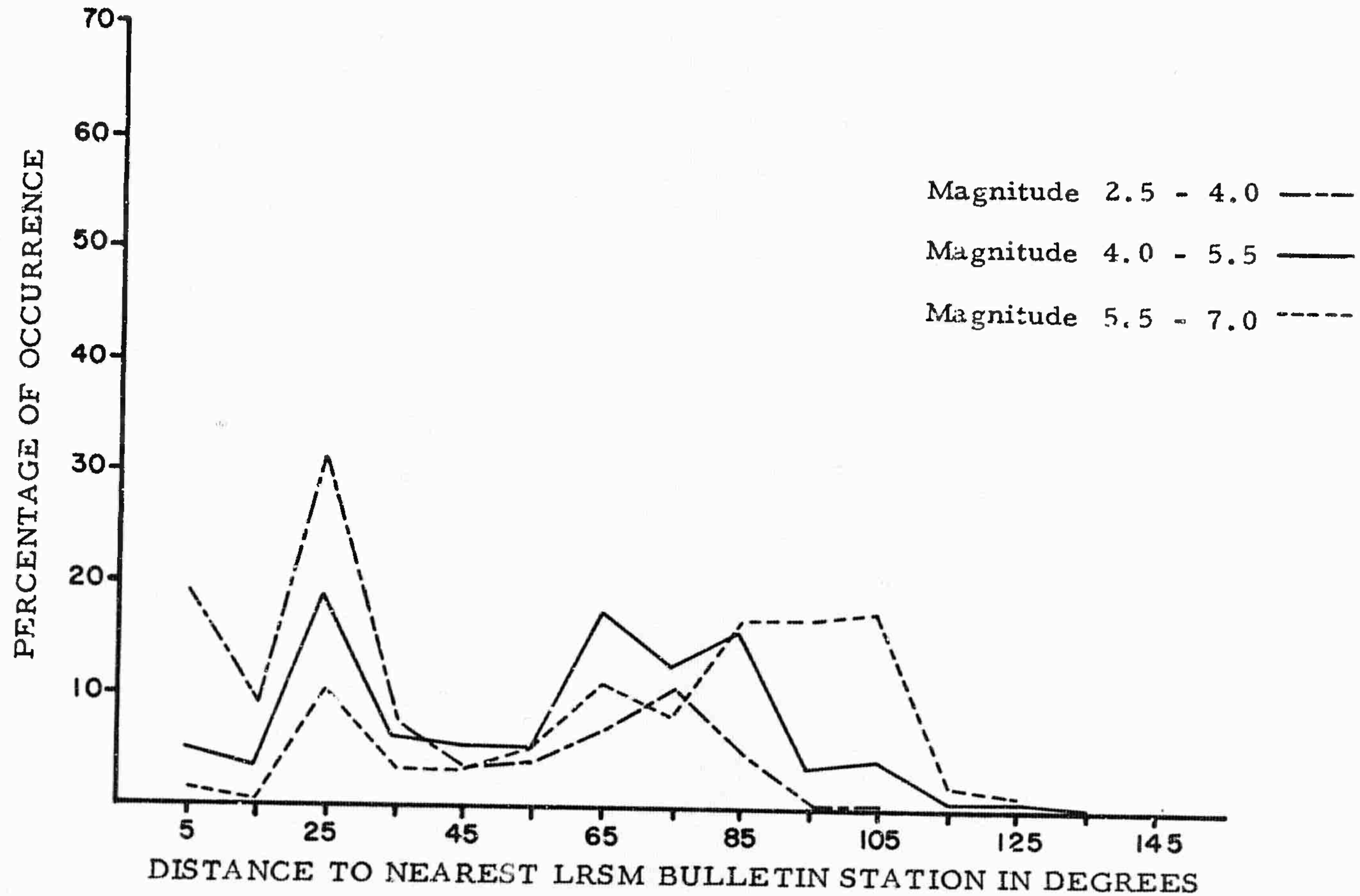


Figure 6. Frequency distributions of epicentral distances from earthquakes

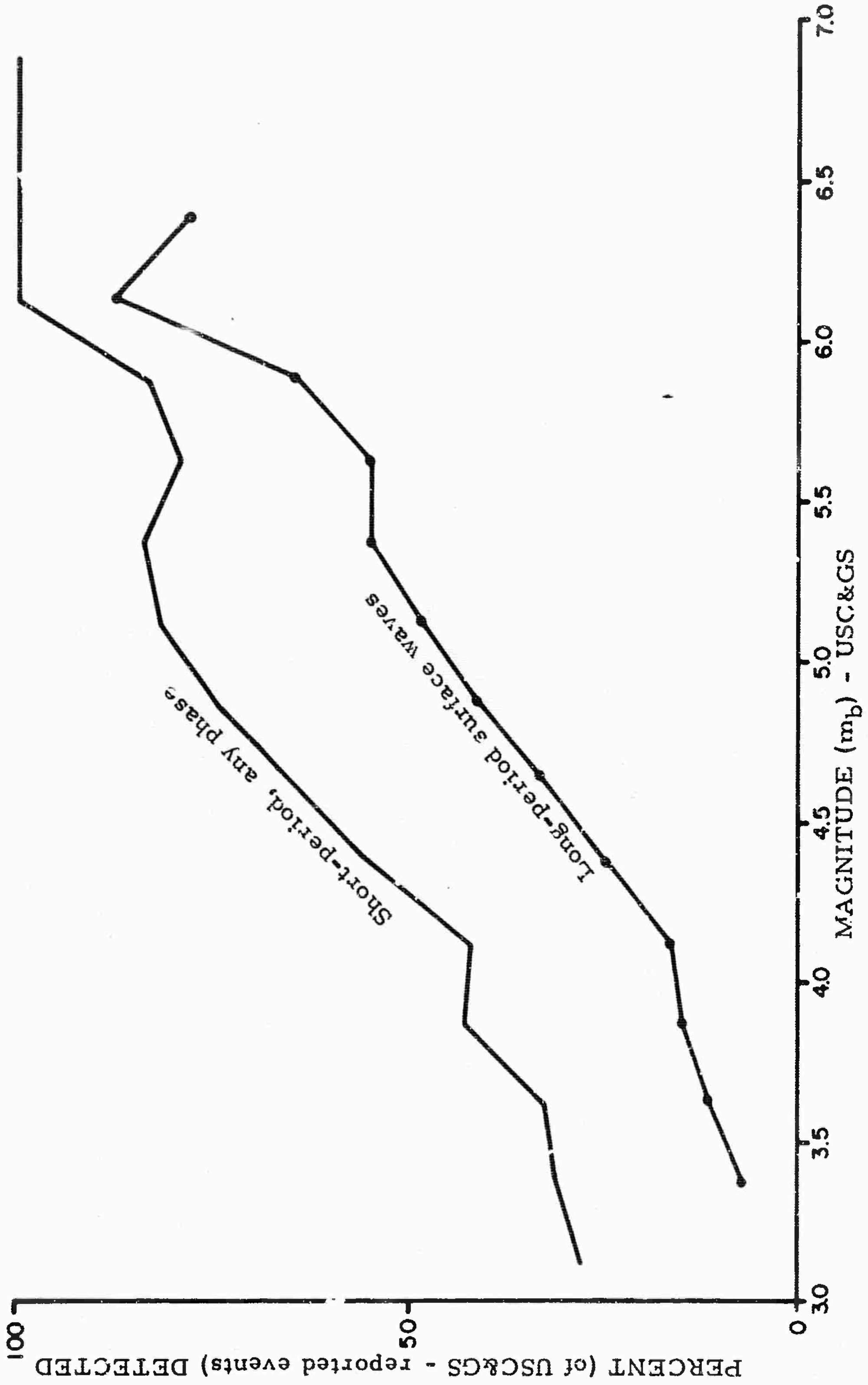


Figure 7. Comparison of short-period and long-period detection functions
(February 1963 - July 1964)

shown in figure 8. As expected, the detection percentages are improved somewhat, although at best by only about 8 percent of all events reported. Note that there is little or no improvement in the small magnitude categories. The improvement in the 6.25-6.50 category suggests that in the unrestricted survey, long-period surface waves were not recorded from several large, deep earthquakes.

## 3. DATA FROM TWO EXCEPTIONALLY HIGH-MAGNIFICATION LRSM BULLETIN STATIONS

### 3.1 DESCRIPTION OF INSTALLATIONS

The LRSM stations at Las Cruces, New Mexico (LC-NM), and La Paz, Bolivia, (LZ-BV), are capable of operating their long-period seismographs at magnifications between 60K and 100K. These magnifications correspond to a normal background trace amplitude of between 5 and 10 mm. Figure 9 shows the typical long-period background at Las Cruces. The normal background is approximately 200 $m\mu$, peak-to-peak, at a period of 15 seconds. Spectra of this noise computed without correcting for the seismograph response typically show dominant period bands at 8 and 15 seconds, the 15-seconds band dominating the other by a factor of about 2 or 3 (see figure 10.) The long-period background at La Paz is similar both in amplitude and frequency content to that at Las Cruces, although the noise band at about 8 seconds is generally less pronounced. A sample of the La Paz long-period background is reproduced in figure 11. The exceptional magnifications (or low noise levels) attainable at these sites are most probably a result of the manner in which the instruments have been installed. The long-period seismometers and amplifiers have been carefully insulated from air movements and from fluctuations in temperature and pressure.

Figure 12 is a sketch of the installation at Las Cruces. This is a mine where both the long-period seismometers and phototube amplifiers are installed in rooms of solid limestone. The door of each room is insulated, and the diurnal temperature variation is on the order of ±1 degree F.

The installation at La Paz, which is depicted in figure 13, utilizes a shallow hole 8 feet square and 30 feet deep dug into solid limestone. The sides of the

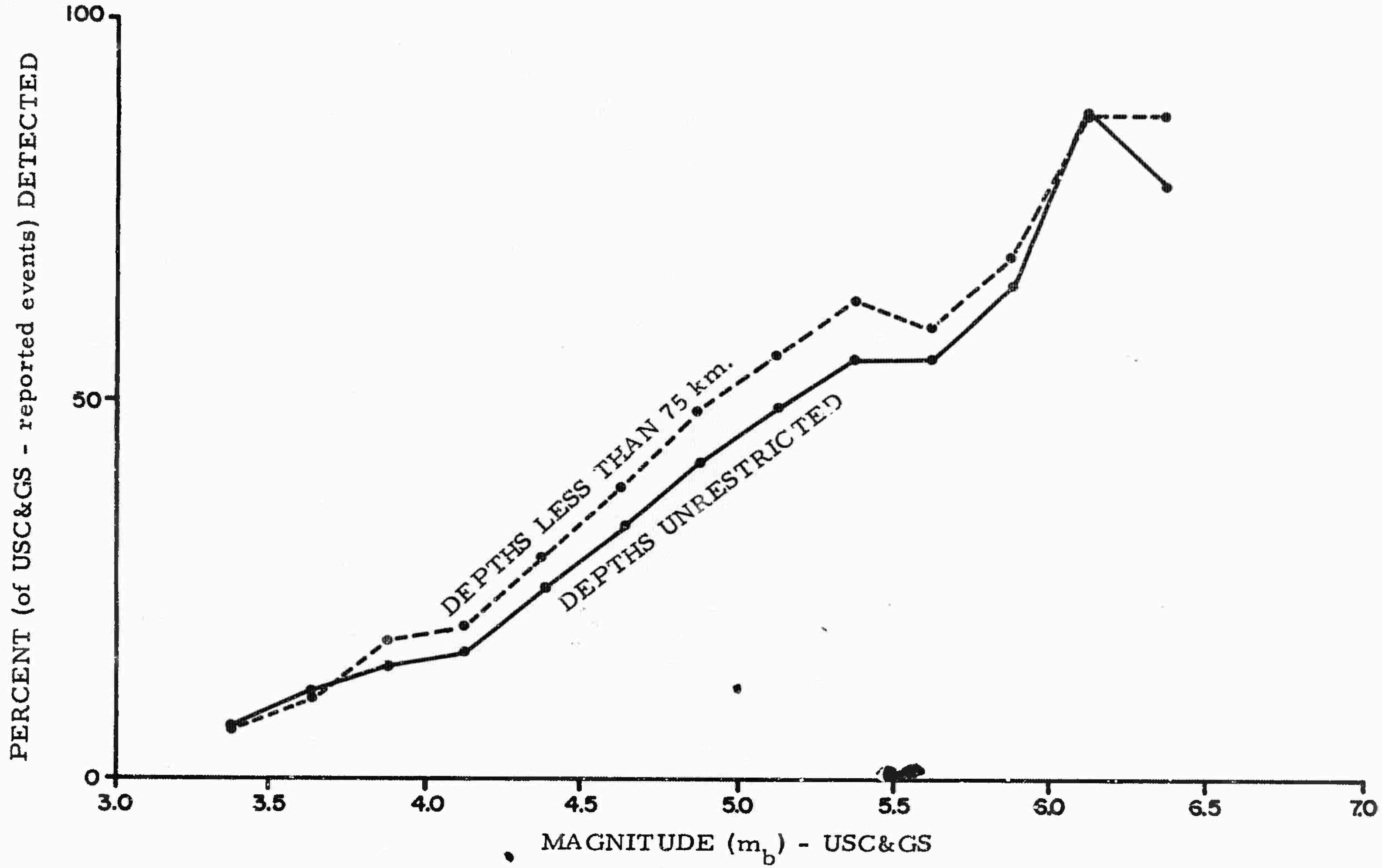


Figure 8. Comparison of long-period surface wave detection functions for events at all depths and at depths less than 75 km. (February 1963 - July, 1964)

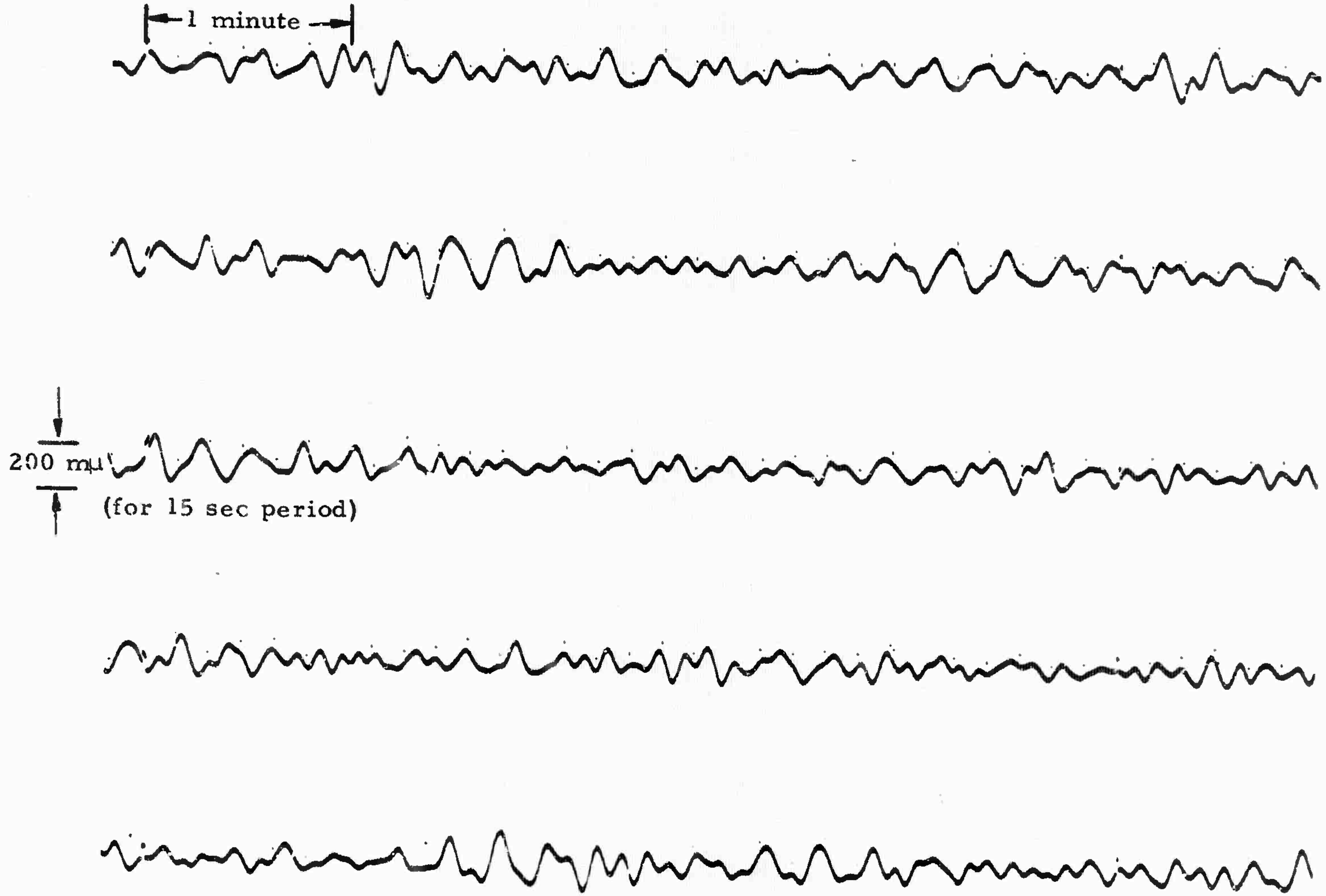


Figure 9. Typical long-period seismic background at Las Cruces, New Mexico (LC-NM) recorded by LRSM vertical seismograph

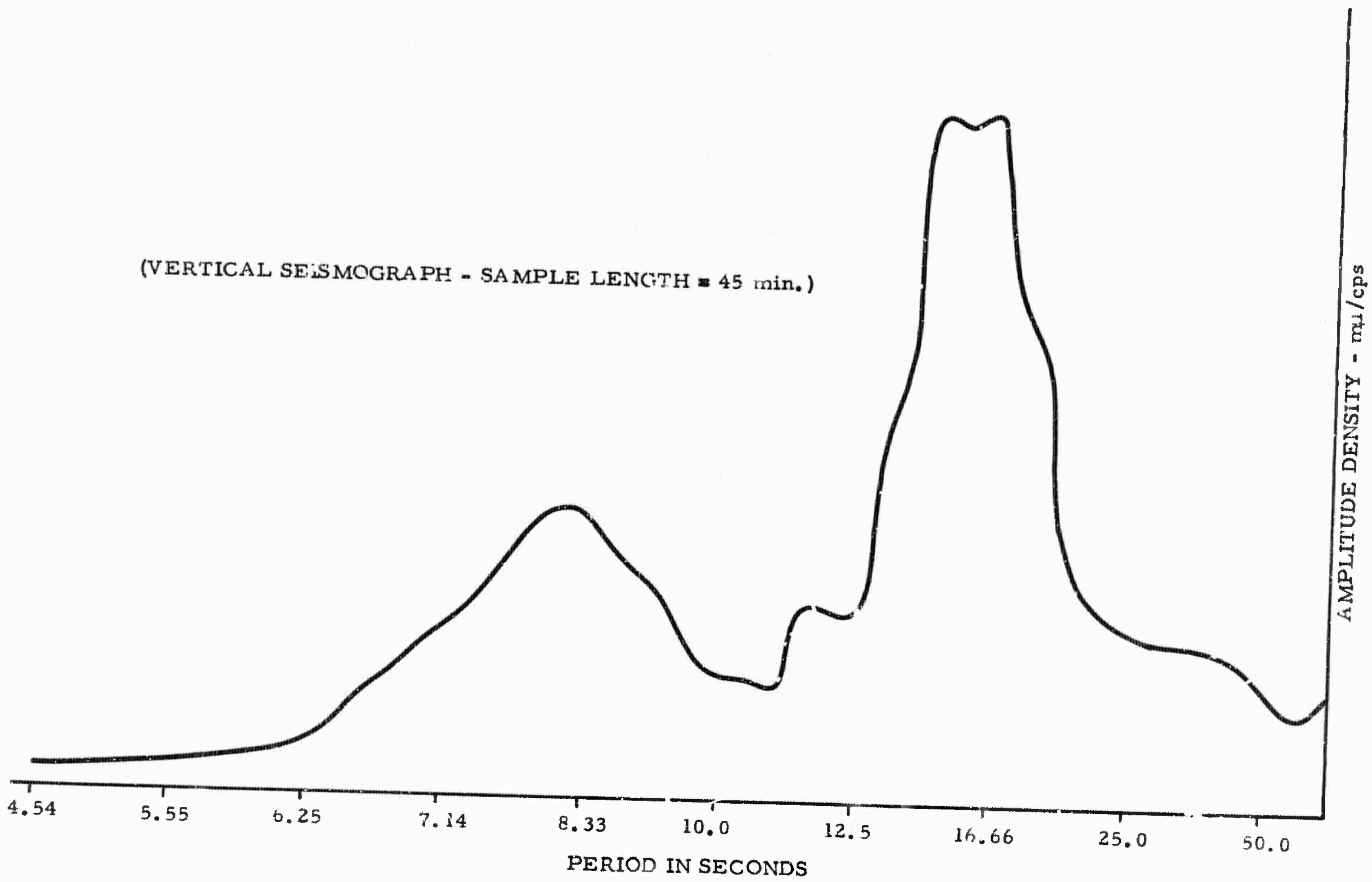


Figure 10. Spectrum of typical long-period seismic background at LC-NM
(Not corrected for seismograph response)

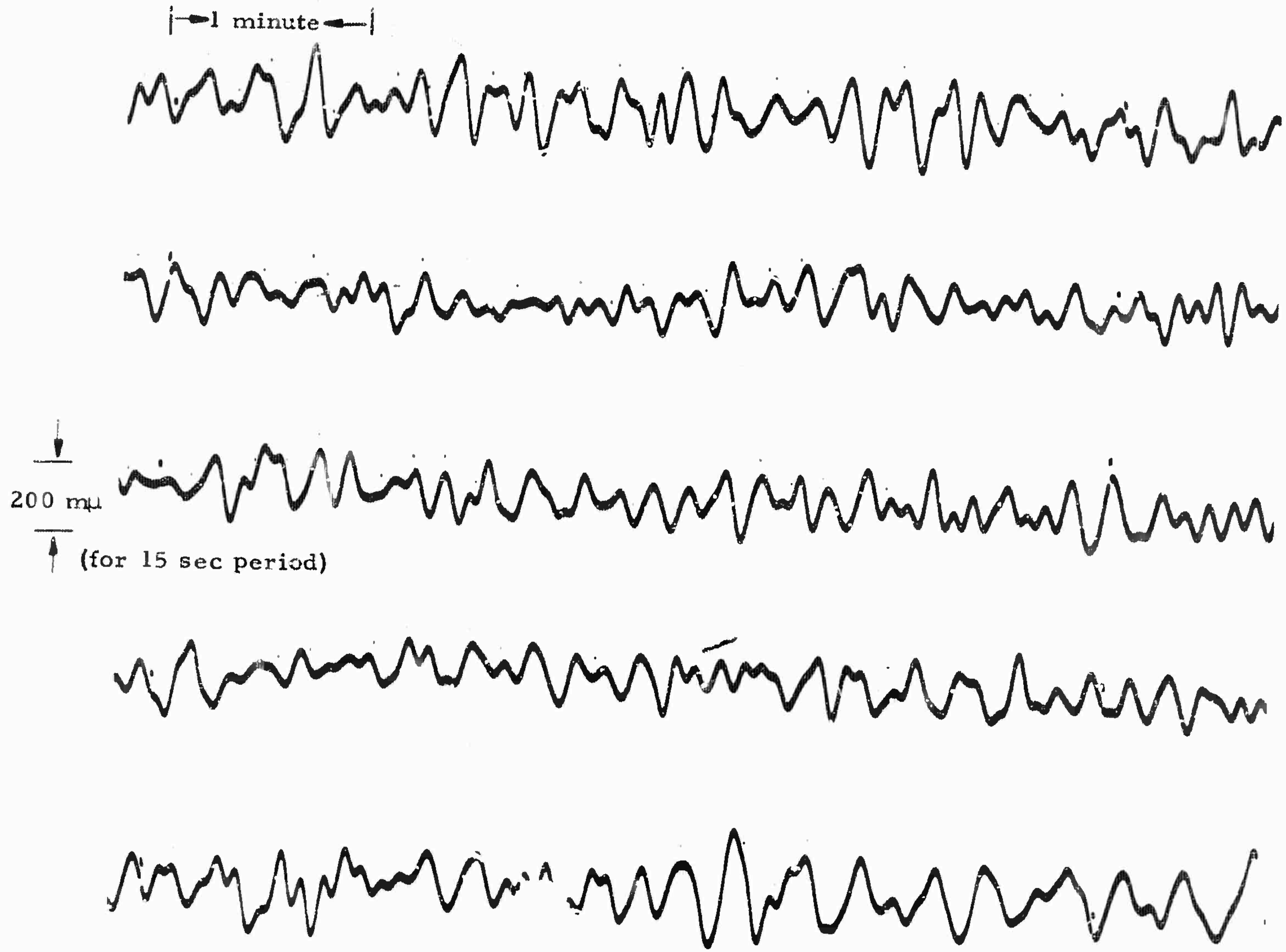


Figure 11. Typical long-period seismic background at La Paz, Bolivia (LZ-BV) recorded by LRSM vertical seismograph

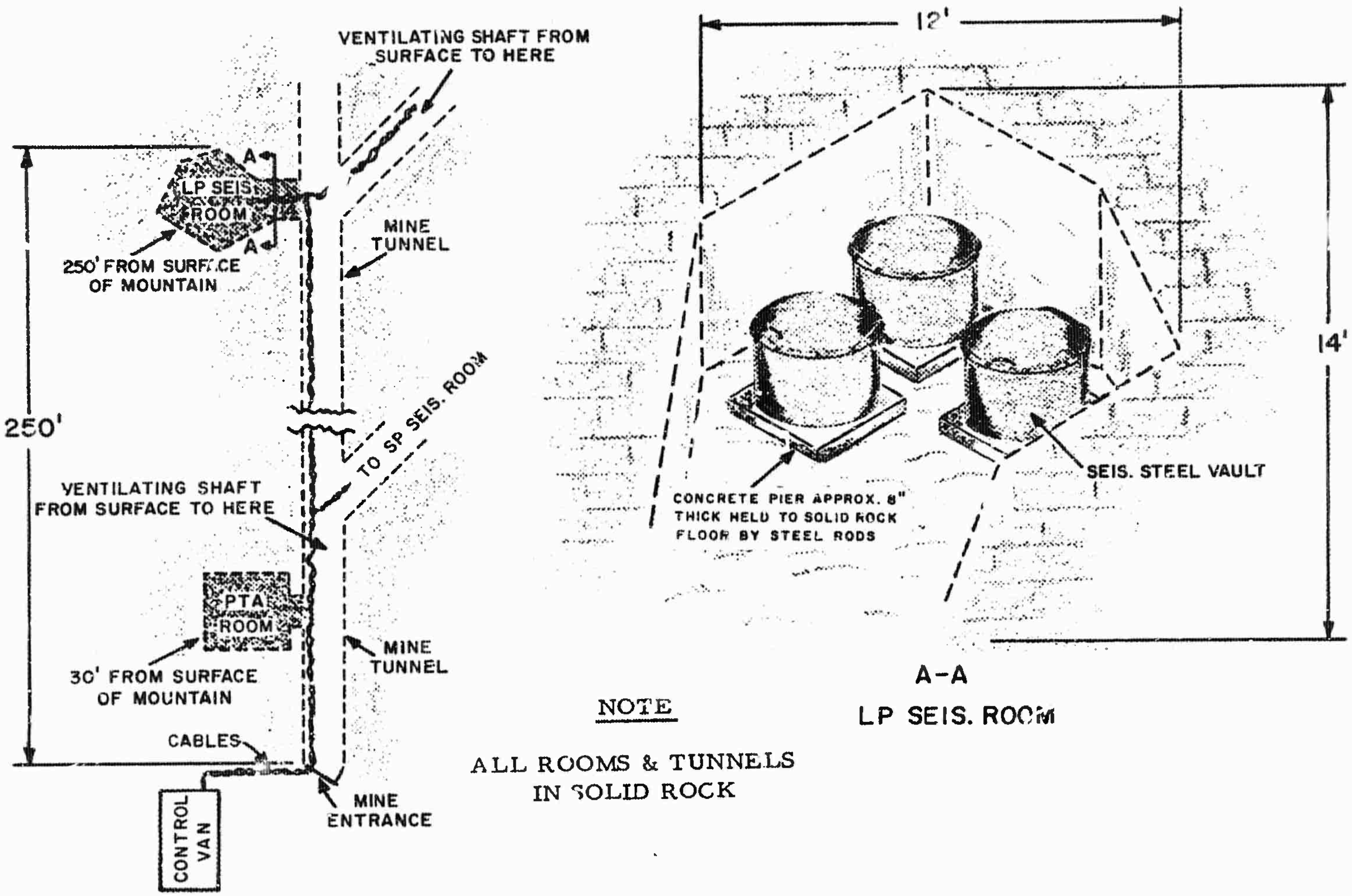


Figure 12. General layout of long-period mine installation Las Cruces, New Mexico

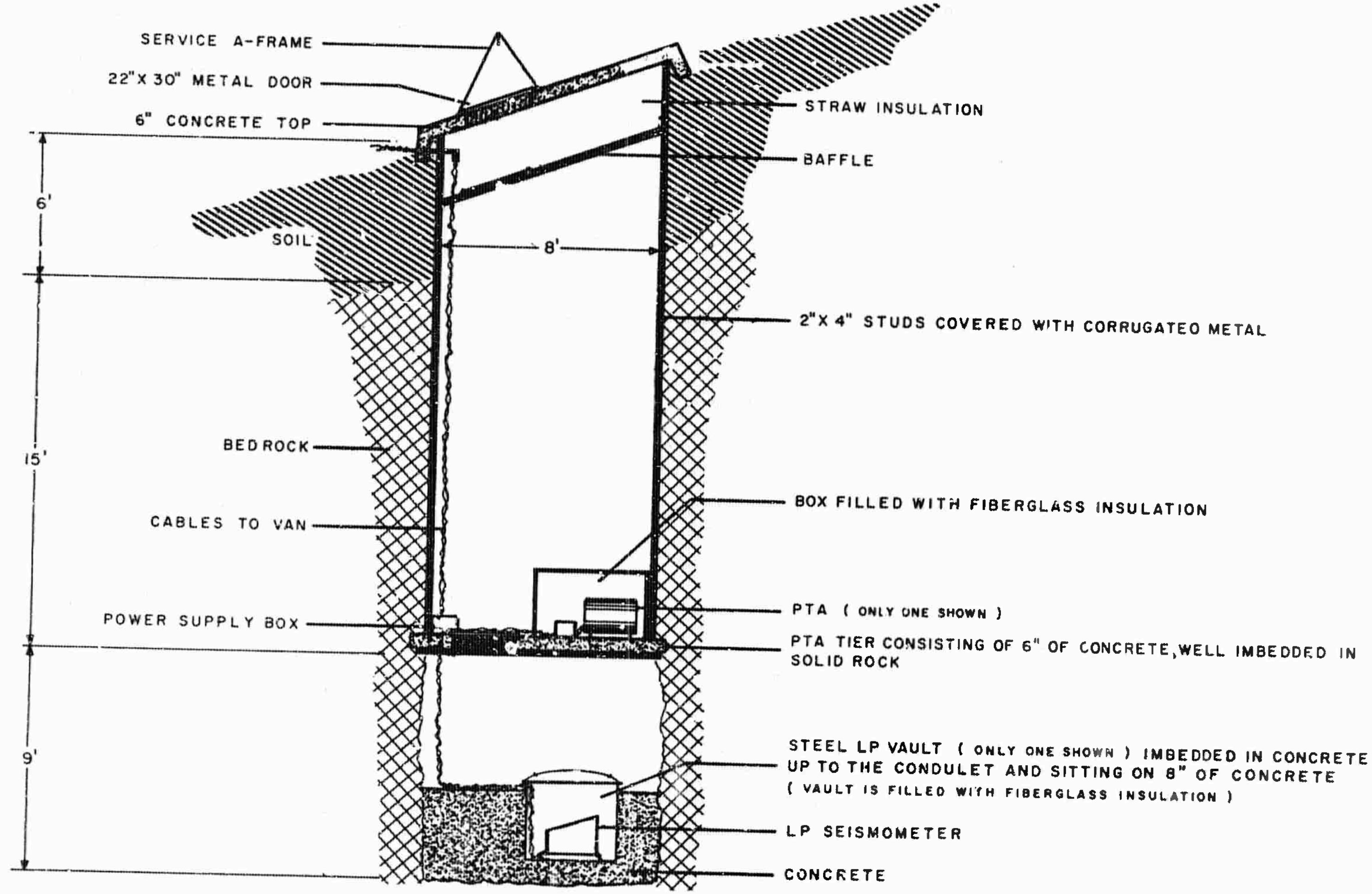


Figure 13. General layout of long-period shallow hole installation
La Paz, Bolivia

hole are lined with wooden beams and corrugated sheet metal. The long-period vaults are imbedded in concrete at the bottom, and the phototube amplifiers (PTA's) are mounted on a platform about 10 feet above the bottom. The PTA platform acts as a baffle for the vault area to minimize convection currents and pressure changes. Temperature in the vicinity of the vaults varies ±1/2°F daily. Prior to installing the instruments in this manner, the same seismographs operating in vaults on the surface were limited by noise to magnifications less than 10K.

## 3.2 ESTIMATES OF DETECTION CAPABILITY

To estimate the detection capability of the LC-NM site for long-period surface waves, a joint distribution graph was computed from the Bulletin data which shows the percentage of events detected as a function of event magnitude and epicentral distance. The basis for the percentages were again the body of events reported by the USC&GS, but only events occurring at depths less than 50 km were considered. The distribution is shown contoured in figure 14. One of the most notable things about it is its erratic shape. This behavior is mainly attributable to a lack of events in certain categories, particularly around the extremes of the magnitude and distance ranges. Nevertheless, it is evident that the detection percentages are not highly sensitive to changes in distance, the event magnitude being a much more controlling factor. Also, it is not particularly unusual to record long-period surface waves from events of around magnitude 4.0 at distances beyond 100°. The distribution in figure 14 is based on 11 months of data, or about 2500 earthquakes.

For purposes of comparison, a similar distribution for the LRSM site at Marysville, California (MV-CL), which operates at a typical long-period magnification of about 22K, is shown in figure 15. One obtains fundamentally the same pattern as for Las Cruces, but with surprisingly little degradation in the overall detection percentages. In spite of the fact that the nominal magnification at Las Cruces is roughly three times what it is at Marysville, the overall detection capability at Las Cruces is only about 1.3 times that at Marysville. This relationship is better illustrated in figure 16, which compares detection versus magnitude functions calculated from the two foregoing distributions. Las Cruces is roughly twice as effective as Marysville in the low-magnitude range but as magnitude increases the percentage improvement afforded by Las Cruces steadily declines, until at a magnitude around 5.8 they both record about 50 percent of all activity. Above this level, MV-CL is generally superior, possibly because of a more favorable geographic location

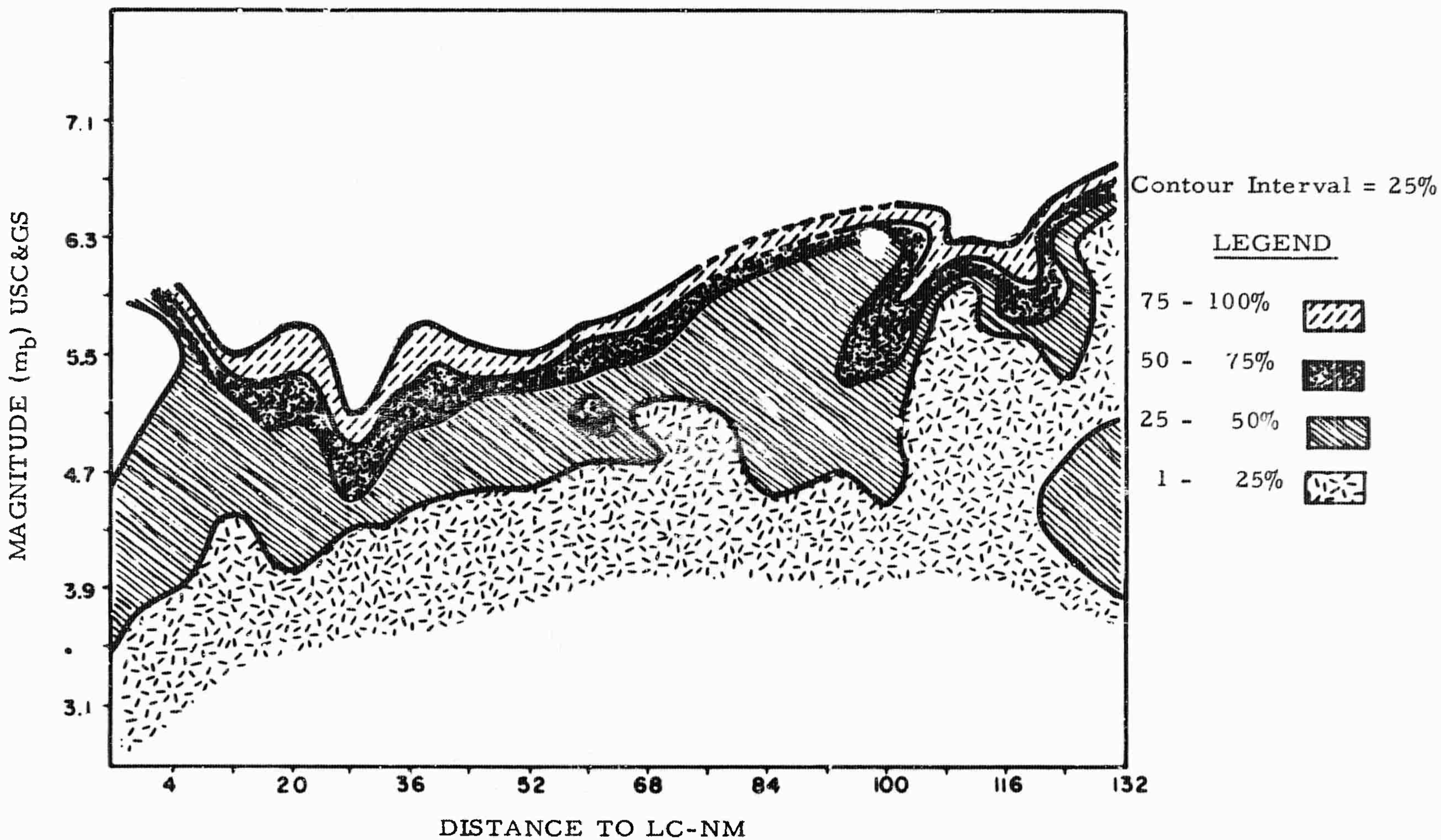


Figure 14. Joint distribution for detection of long-period surface motion at LC-NM

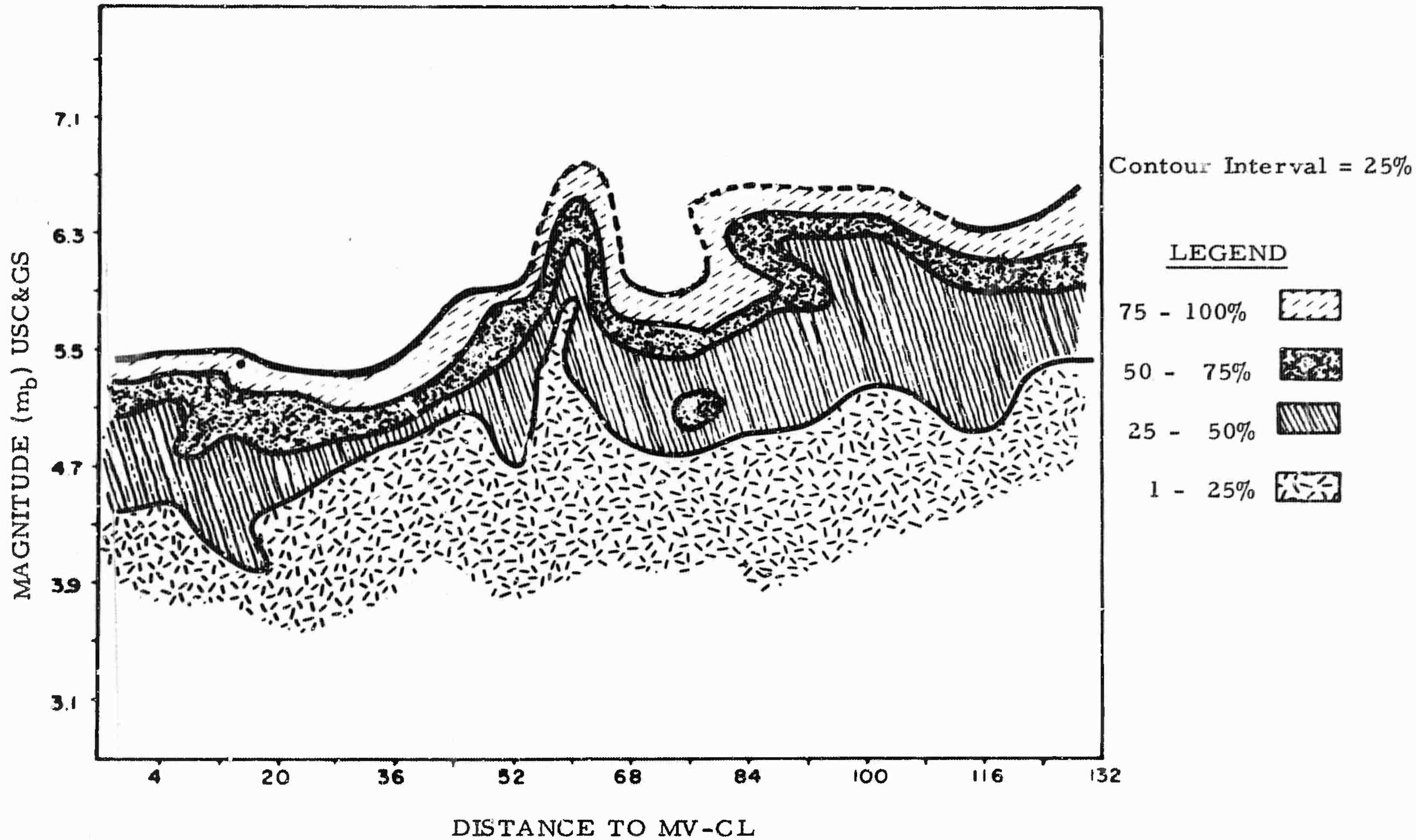


Figure 15. Joint distribution for detection of long-period surface motion at MV-CL

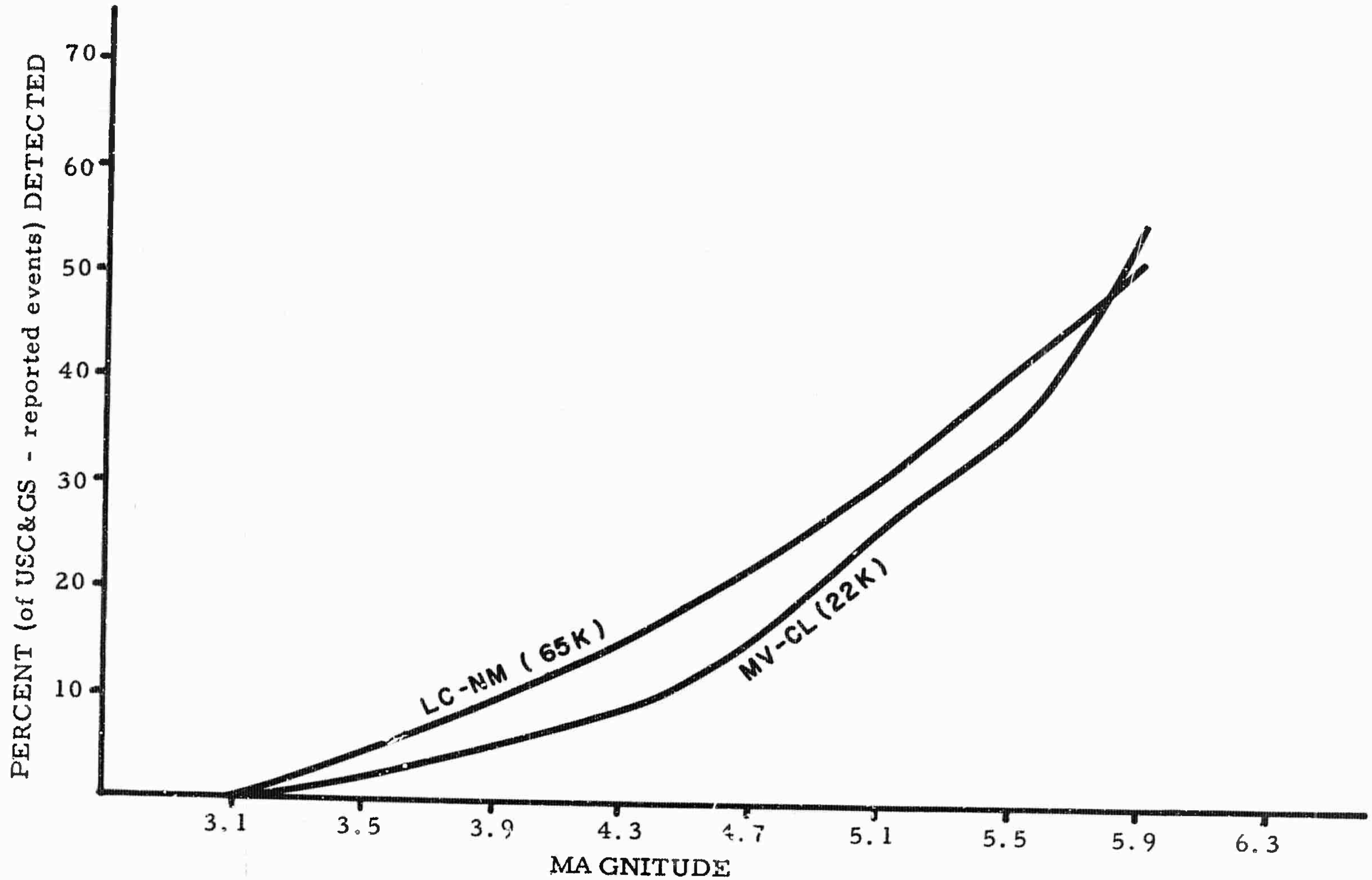


Figure 16. Relative detection capability for long-period surface waves
LC-NM (65K) vs MV-CL (22K)
(For all distances - depth restricted to 50 km or less)

relative to the major seismic areas. Thus in terms of percentage improvement one obtains the greatest benefit from increased seismograph magnification at the lowest magnitudes. Evidently, whether one does or does not record long-period surface waves at a certain site from a shallow event of given magnitude is affected to a degree by some variable other than seismograph magnification. This variable is most probably connected with either the earthquake mechanism, i.e. - its radiation pattern, or the path that must be traveled by the waves. One would expect a network of stations to be more immune to these variables, and this is borne out by the superiority of the Bulletin network function shown in figure 4.

## 4. DATA FROM VELA-UNIFORM OBSERVATORIES

### 4.1 GENERAL

The purpose of this study was to provide a measure of the percentages of Rayleigh waves that are currently being detected at the five VELA-UNIFORM seismological observatories operating in the United States. Figure 17 shows the locations of the five observatories. Information concerning the phases reported by each of the observatories and the associated epicenters located by the USC&GS is stored on magnetic tapes. These tapes served as the input data for the study.

### 4.2 METHOD

If a Rayleigh wave is detected at any observatory, one of the instruments making the detection is invariably the long-period vertical seismograph. For ~~this reason, the long-period~~ vertical seismograph is used in this study as the Rayleigh wave detector. Figure 18 shows the period response of the standard long-period seismograph used at the observatories. The peak response is at a period of 30 seconds.

All Rayleigh waves that were associated with a USC&GS epicenter and were detected at BMSO, UBSO, WMSO, or CPSO during the period February 1963 through August 1964 were classified and counted according to epicentral distance, USC&GS magnitude of the event, and the magnification of the recording seismograph. All associated Rayleigh waves detected at TFSO during the period April 1964 through August 1964 were similarly classified and counted.

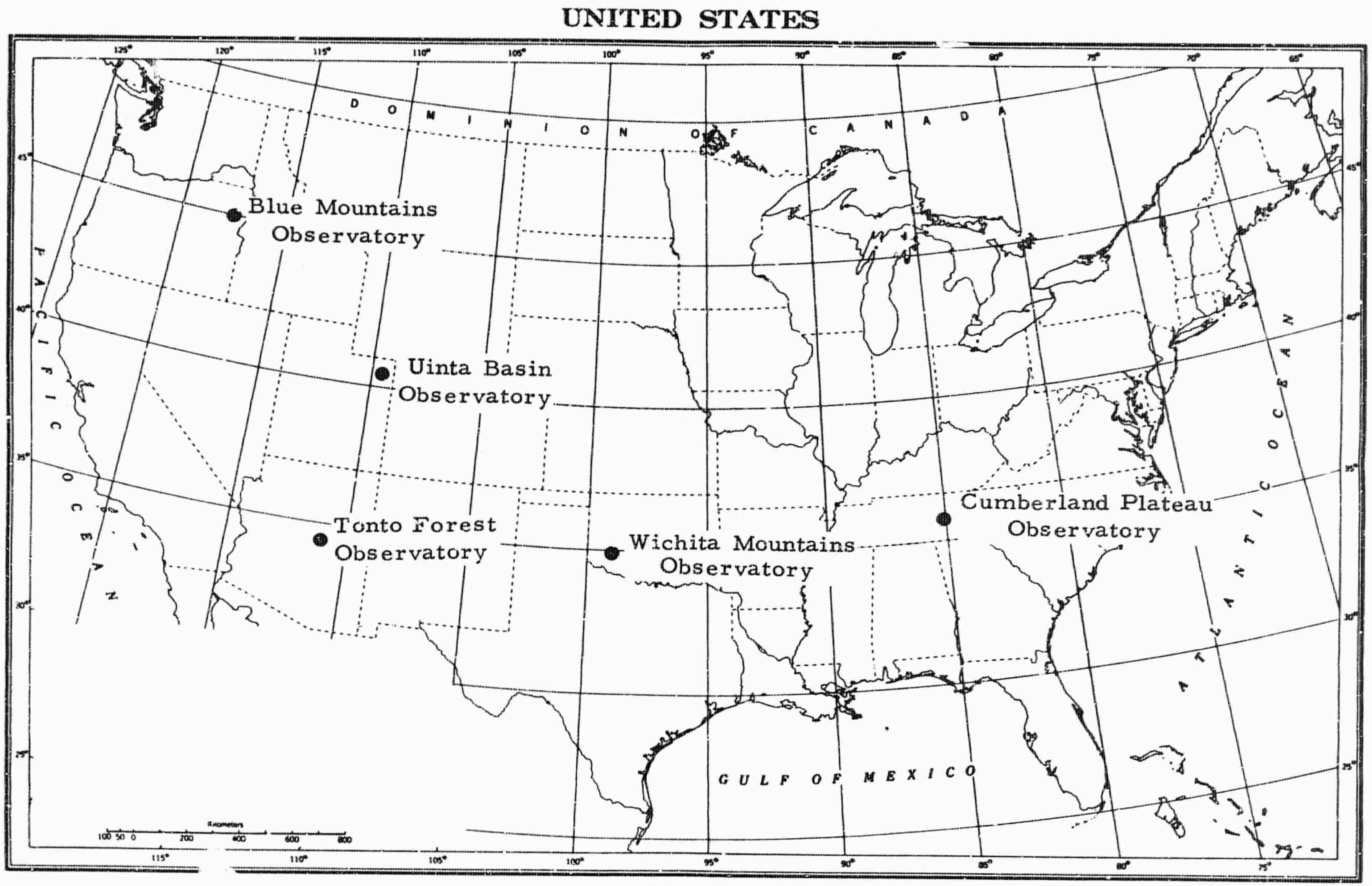


Figure 17. Locations of the VELA-UNIFORM Seismological Observatories

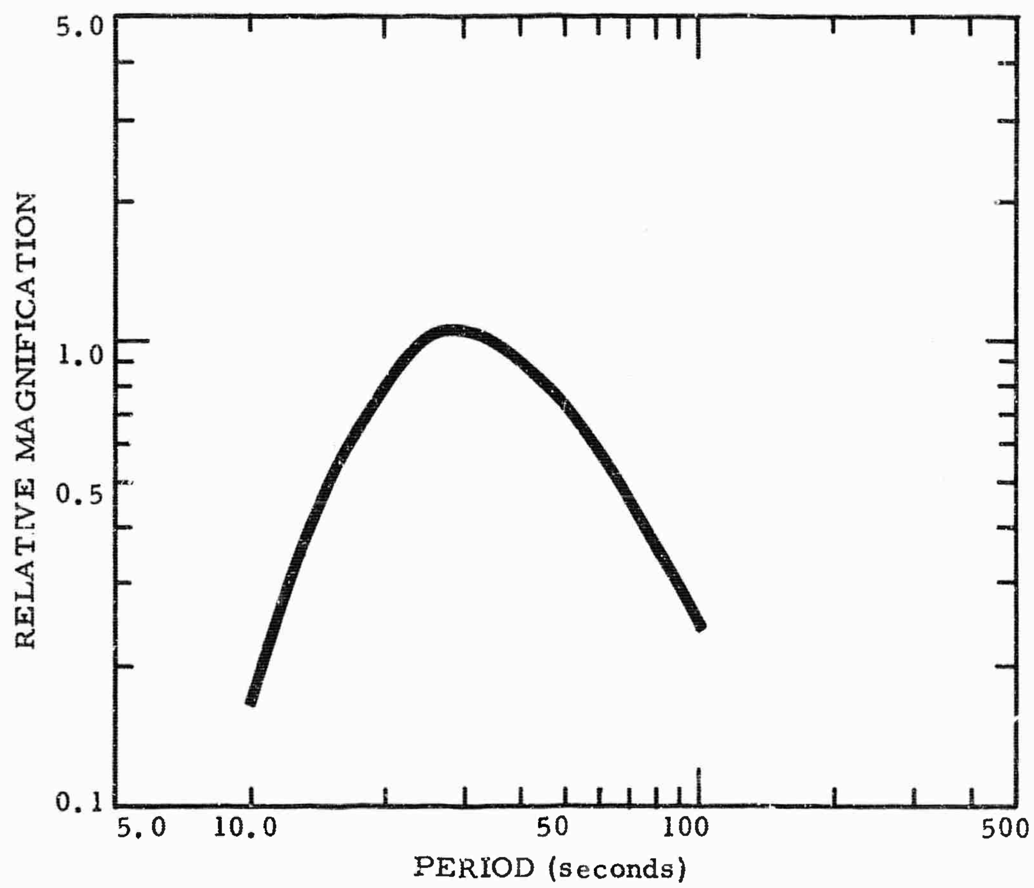


Figure 18. Standard long-period seismograph period response

The detection count was made in a three-dimensional array in which the three variables constituted the coordinate axes. The individual cells in the array consisted of 8 degree distance intervals, 0.2 unit magnitude intervals, and approximately 10K magnification intervals with midpoints at 10K, 20K, and 30K.

In order to obtain a detection percentage, each shallow and intermediate-depth (less than 300 km) event located by the USC&GS was classified and counted in the same manner as the Rayleigh detections. Since arrivals at five observatories were considered, it was assumed that each event produced five possibilities for recording a Rayleigh wave. For each event, the magnitude was noted, the distances from the epicenter to each of the five stations were calculated, and the magnification of the recording seismograph at each station for that particular time was determined. Each of these five occurrences was then counted in its proper cell in the array. By dividing the contents of the cells in the Rayleigh-wave array by the contents of the corresponding cells in the earthquake-occurrence array, a detection percentage as a function of distance, magnitude, and magnification was established.

## 4.3 RESULTS

Figure 19 shows percent detection as a function of magnitude for instruments operating at a magnification of 10K. All magnifications are for a period of 25 seconds. The number of occurrences for each magnitude interval is given above each bar of the graph; these numbers are a good measure of the confidence that can be placed in each percentage determination. As expected, there is a general increase in percent detection with increasing magnitude. The number of occurrences is much greater near the center of the magnitude range than at each end. It is therefore possible that the anomalous detection percentages at magnitudes less than 3.4 and greater than 6.0 are due to the very small number of samples available.

Figure 20 shows percent detection as a function of magnitude for instruments operating at a magnification of 20K. In the middle magnitudes, where there are a large number of occurrences, the increase in detection percentage with increasing magnitude is approximately linear.

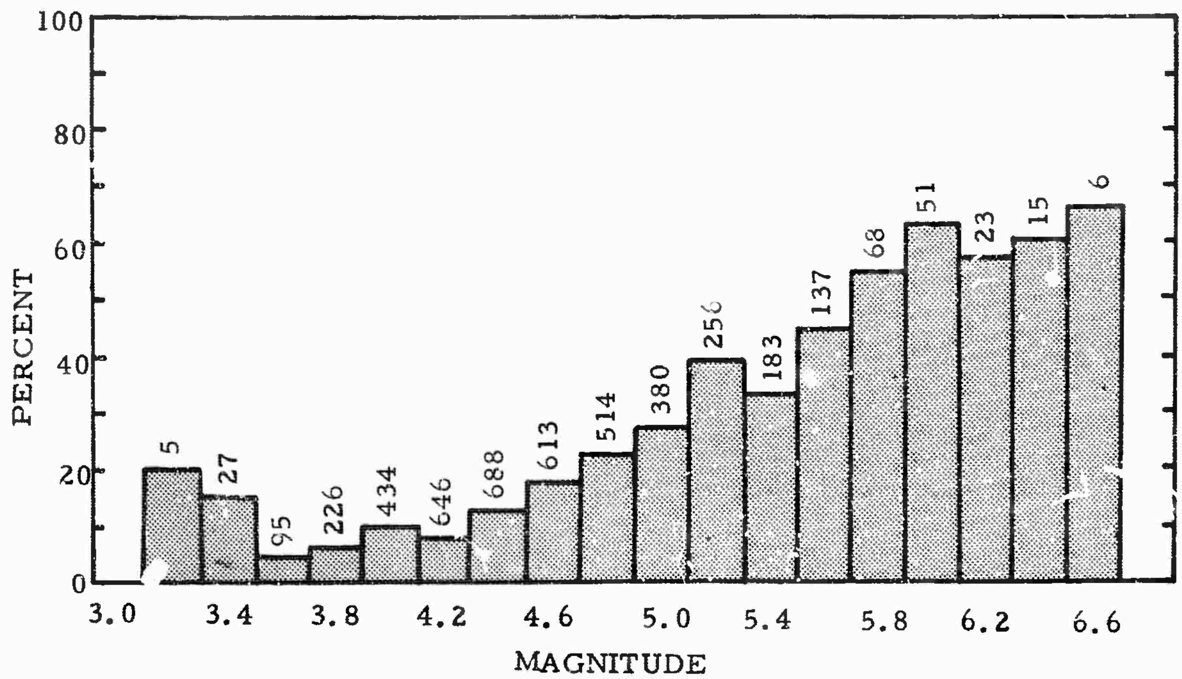


Figure 19. Percent detection of Rayleigh waves - magnification = 10K

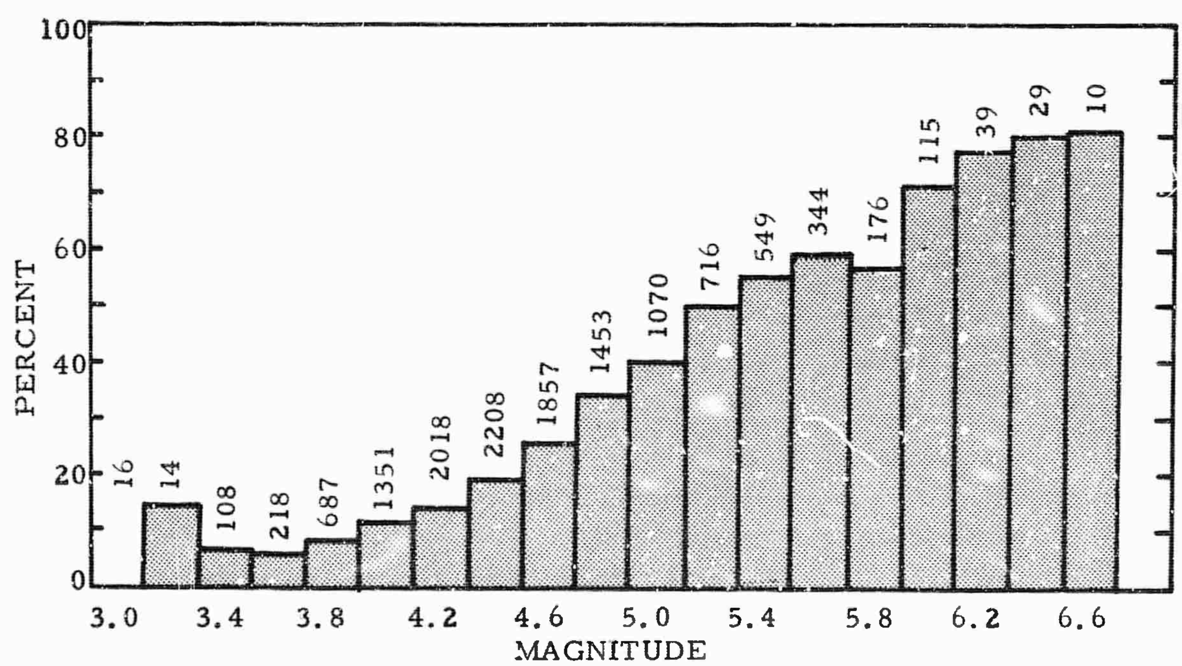


Figure 20. Percent detection of Rayleigh waves - magnification =20K

Figure 21 shows percent detection for instruments operating at a magnification of 30K. In this case the detection percentages corresponding to the extreme magnitudes conform with the general trend established by the middle magnitudes. This is evidently due to chance rather than to any effects of increasing magnification, because the number of samples in the extreme magnitudes is no larger than it was at lower magnifications.

Figure 22 shows a significant increase in percentage of detections with increasing magnification, most of the increase coming in the jump from 10K to 20K.

Figure 23 shows the 50 percent detection level as a function of distance and magnitude at a magnification of 10K. The 50 percent level is the only level at which any confidence can be expressed. Higher levels involve combinations of distance and magnitude at which there are insufficient samples. Figure 24 shows a similar plot for instruments operating at a magnification of 20K. There is a noticeable insensitivity of percent detection to epicentral distance. For example, at magnitude 5.0, the detection percentage of Rayleigh waves is almost as great at 90 degrees as it is at 50 degrees. Figure 25 shows the 50 percent detection level for instruments operating at a magnification of 30K. Figure 26 demonstrates the effect on the 50 percent detection level of increasing the magnification. For closer distances there appears to be little improvement. This is partly due to the difficulty in distinguishing Rayleigh from Love waves at distances less than 20 degrees; if there was an obvious surface arrival that could not be identified definitely as Rayleigh, it was not counted as a Rayleigh detection in this study. Therefore, the main detection problem in this distance range is not one that readily responds to an increase in operational magnification.

## 5. CONCLUSIONS

Considering the differences in the survey schemes employed, as well as the analysis philosophies used in compiling the two bulletins, the results of the separate studies are in good agreement. Both the LRSM data and the VELA-UNIFORM observatory data show that there is a continuous decline in the detection percentage of long-period surface waves as the magnitude becomes smaller than 4.0. This would not be true if earthquakes of magnitude less than 4.0 did not generate surface waves, or if they generated them

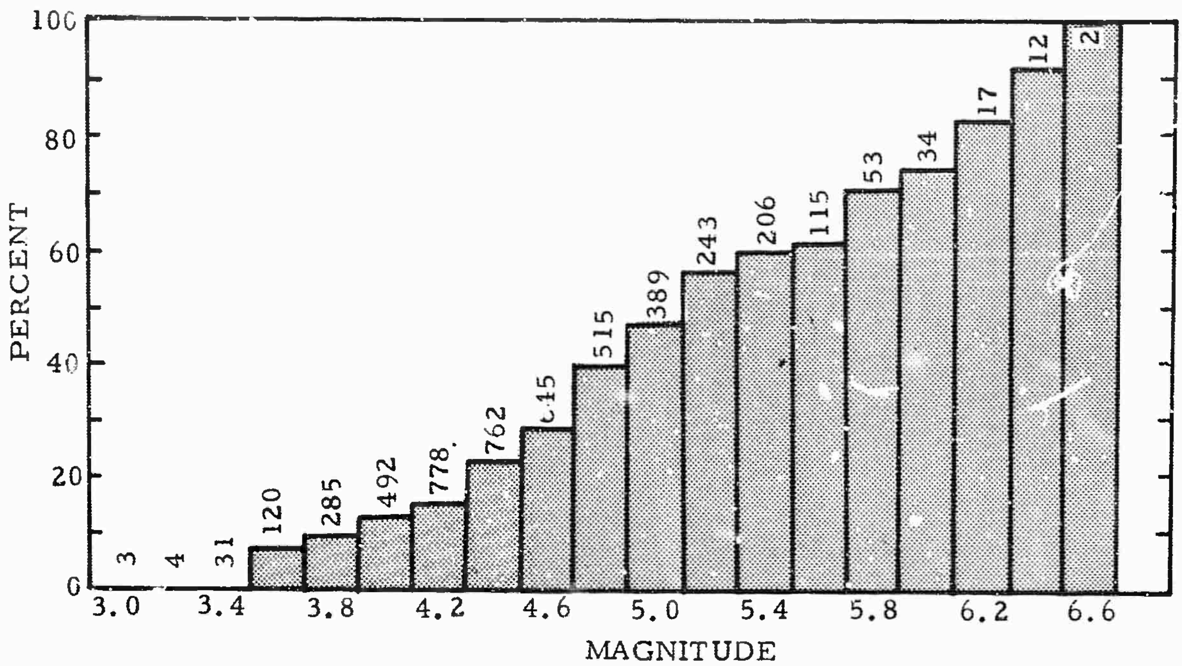


Figure 21. Percent detection of Rayleigh waves - magnification = 30K

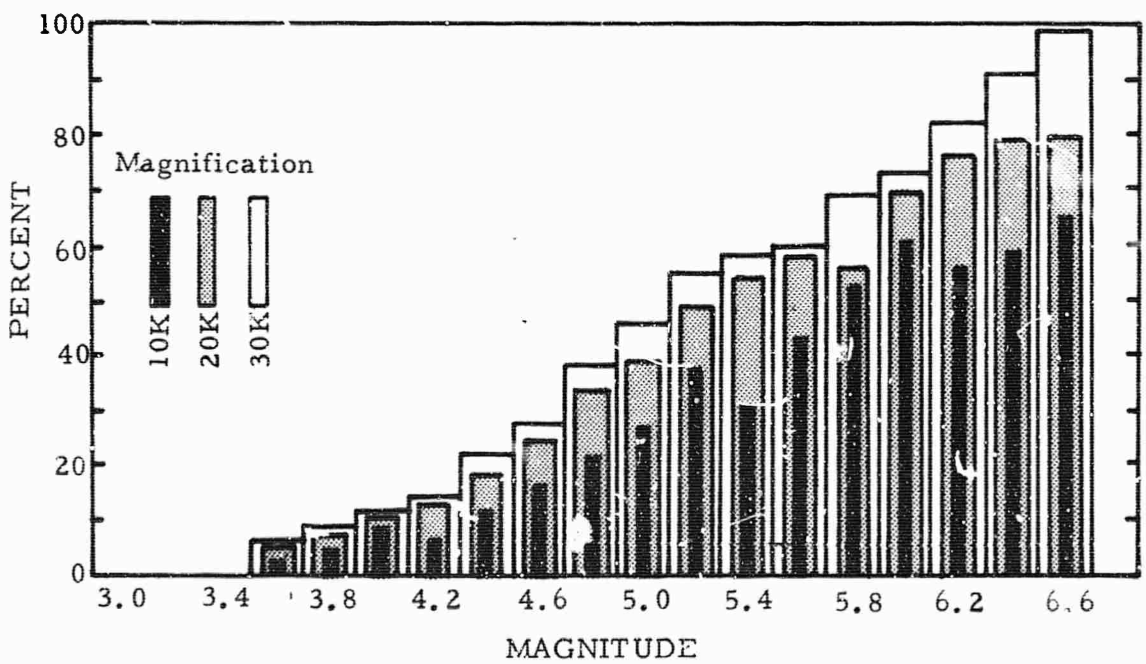


Figure 22. Percent detection of Rayleigh waves (all magnifications)

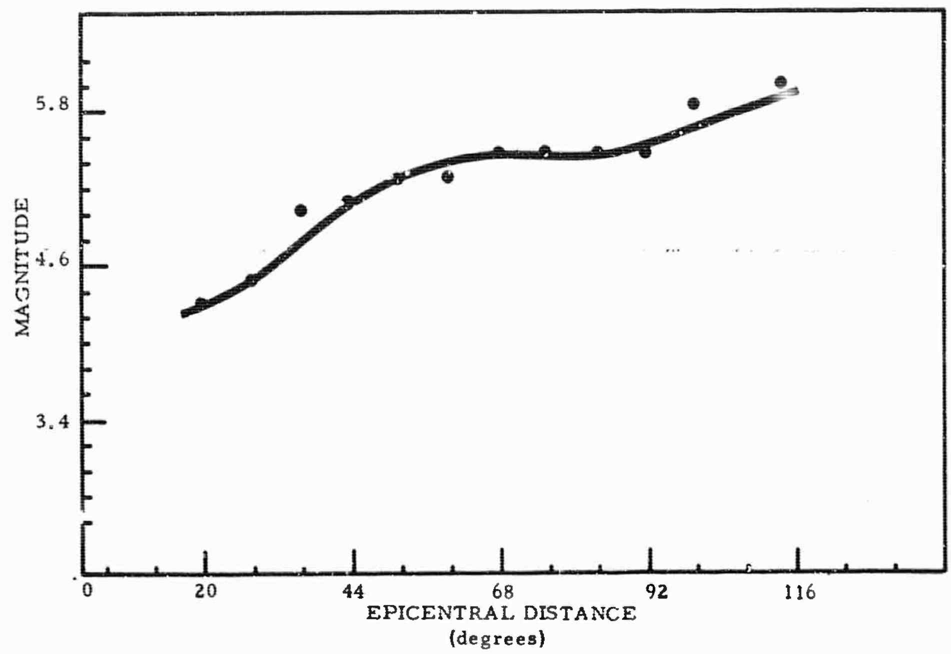


Figure 23. Fifty percent detection level for Rayleigh waves recorded by long-period instruments - magnification = 10K

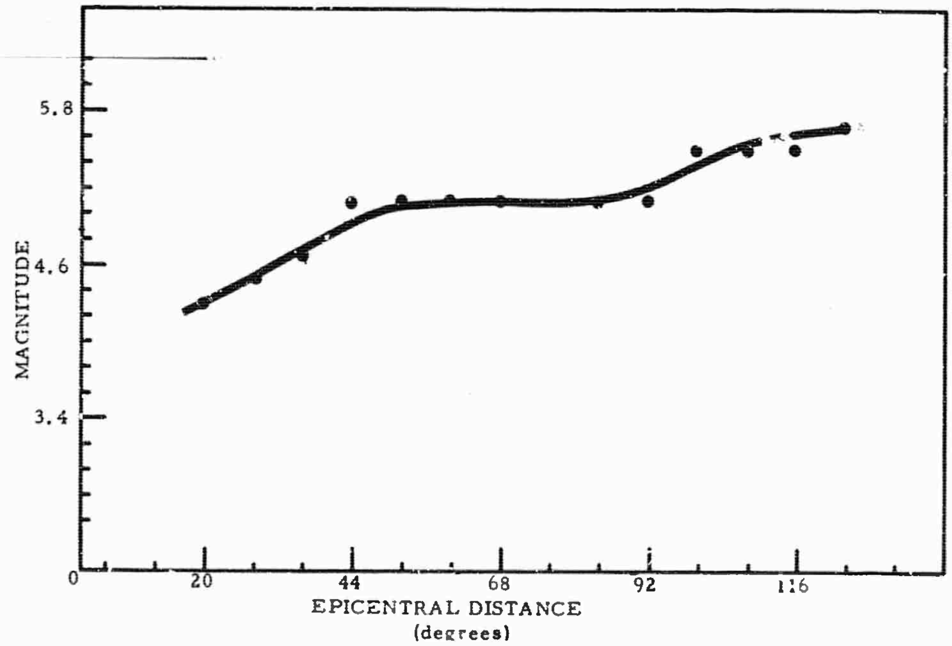


Figure 24. Fifty percent detection level for Rayleigh waves recorded by long-period instruments - magnification= 20K

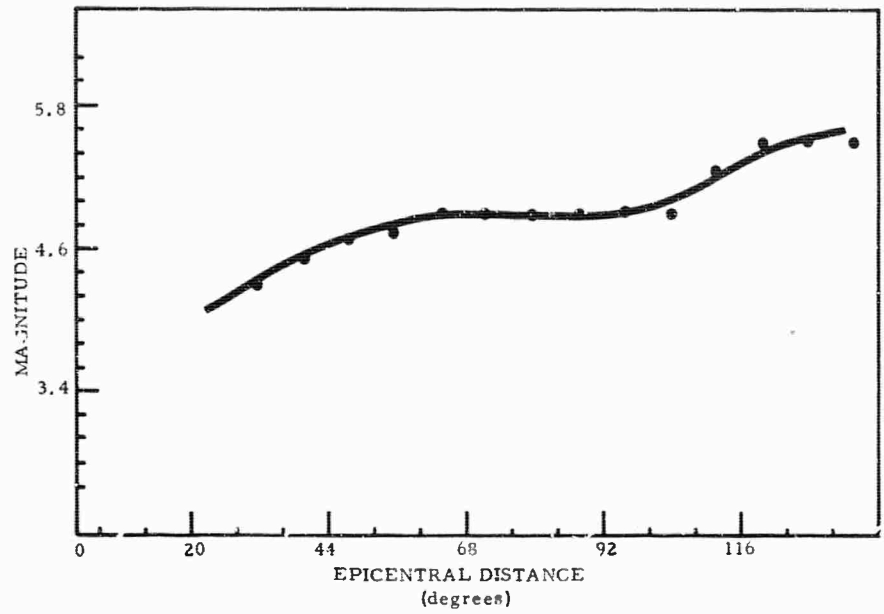


Figure 25. Fifty percent detection level for Rayleigh waves recorded by long-period instruments - magnification = 30K

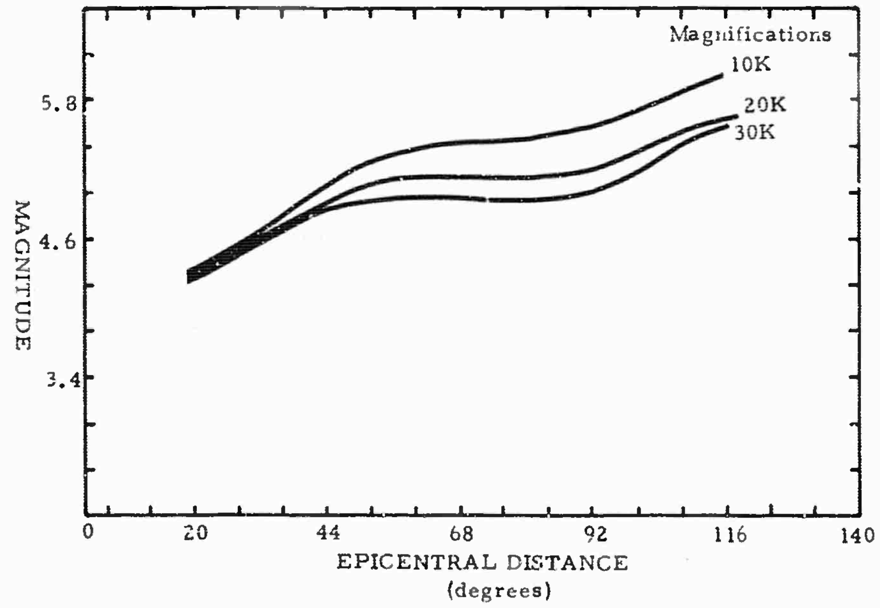


Figure 26. Fifty percent detection level for Rayleigh waves recorded by long-period instruments (all magnifications)

significantly less efficiently than do larger magnitude earthquakes. In this case, there would be a discontinuity or a sharp change of slope in the curve. It is therefore concluded that earthquakes at least as small as magnitude 3.2 generate surface waves.

The increase in percent detection with increasing magnitude is much closer to linear than to exponential. This is especially true in the magnitude range 3.6 to 6.0 where a great number of samples permit the calculation of percentages with a good degree of confidence. At magnitudes below 3.6 and above 6.0, there is a leveling off of the detection curve. This may be real or it may be a result of the small number of samples available at these magnitudes.

The percent detection of long-period surface waves is less sensitive to distance changes than to magnitude changes. A change in 0.2 unit of magnitude almost always results in a noticeable change in detection percentage. A 10 degree distance change, however, will usually cause very little change in detection percentage.

An increase in seismograph magnification is seldom accompanied by a proportionate increase in the percentage of surface waves detected. The greatest increase is obtained in the lower magnitude categories.

It should be noted that many surface waves are detected with which no epicenter can be associated. Also, many surface waves are not detected because they arrive in the wave train of another event. If these two factors could be weighted and integrated into a detection study, a somewhat more accurate measure of current detection capability could be determined.