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SEISMIC SHEAR WAVES AS A DISCRIMINANT BETWEEN EARTHQUAKES AND UNDERGROUND NUCLEAR EXPLOSIONS

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5 JULY 1972

Prepared for
AIR FORCE TECHNICAL APPLICATIONS CENTER
Washington, D.C.

Under
Project VELA UNIFORM

Sponsored by
ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Monitoring Research Office
ARPA Order No. 1714

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SEISMIC DATA LABORATORY REPORT NO. 295

AFTAC Project No.:	VELA T/2706
Project Title:	Seismic Data Laboratory
ARPA Order No.:	1714
ARPA Program Code No.:	2F-10
Name of Contractor:	TELEDYNE GEOTECH
Contract No.:	F33657-72-C-0009
Date of Contract:	01 July 1971
Amount of Contract:	$ 1,314,000
Contract Expiration Date:	30 June 1972
Project Manager:	Robert R. Blandford (703) 836-3882

P. O. Box 334, Alexandria, Virginia

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Unclassified
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Teledyne Geotech Alexandria, Virginia	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b GROUP

3 REPORT TITLE
SEISMIC SHEAR WAVES AS A DISCRIMINANT BETWEEN EARTHQUAKES AND UNDERGROUND NUCLEAR EXPLOSIONS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Scientific

5. AUTHOR(S) (Last name, first name, initial)
von Seggern, D.H.

6. REPORT DATE 5 July 1972	7a. TOTAL NO. OF PAGES 27	7b. NO. OF REFS 12
8a. CONTRACT OR GRANT NO. F33657-72-C-0009 b. PROJECT NO. VELA T/2706 ARPA Order No. 1714 d. ARPA Program Code No. 2F-10	9a. ORIGINATOR'S REPORT NUMBER(S) 295 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	

10. AVAILABILITY/LIMITATION NOTICES

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

11 SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Advanced Research Projects Agency Nuclear Monitoring Research Office Washington, D.C.

13 ABSTRACT
The theoretical amplitude ratio of shear waves to compressional waves is computed using point double-couple representations of earthquakes. These ratios are compared to earthquake data from the LRSM and VELA observatory network. The earthquake data on shear-to-compressional ratios from this network is directly compared to that from NTS underground nuclear explosions. The shear-to-compressional ratio in the teleseismic distance range is found to be significantly greater for earthquakes than explosions, especially in the short-period band. However, use of shear wave data to discriminate between earthquakes and explosions is hampered by a high detection threshold.

14 KEY WORDS
Shear Waves
Love Waves
Seismic Discrimination

Unclassified
Security Classification

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INTRODUCTION

In a layered half-space, a purely dilatational source mechanism such as a buried explosion should theoretically produce no horizontally-polarized shear waves and only a small amount of vertically-polarized shear waves. In contrast, all proposed earthquake mechanisms for shallow sources do entail shear-wave generation. Thus, the use of shear waves to discriminate between natural seismic events and underground nuclear detonations is a logical proposal. Use of this discriminant is severely restricted because we observe shear waves of some mode for most explosions due either to inhomogeneities in the earth or to ambient shear stress influences at the detonation site and because there is a high detection threshold for shear waves.

Many authors have previously reported a higher ratio of shear-to-compressional displacement for earthquakes than for explosions (Press et al. 1963; Willis et al., 1963; DeNoyer, 1966; Booker and Mitronovas, 1964; Pasechnik, 1970). The purpose of this report is to add to our knowledge of the relative excitation of shear waves by earthquakes and by underground nuclear explosions. We do not report here on a unified project for S wave discrimination but rather on a few short studies which were made over a period of years at the Seismic Data Laboratory and which are pertinent to this topic.

THEORETICAL EXCITATION OF COMPRESSIONAL AND SHEAR WAVES

For an ideal, spherically symmetric, compressional source of elastic waves, the displacement at the source is entirely radial in a homogeneous medium, and thus an explosion should emit no shear waves. For an earthquake, however, shear dislocation along a fault plane is the accepted model for all but deep events, and thus shear waves are emitted. Only the fact that the dislocation must end at some point in space requires compressional waves to be generated by the earthquake model. If we consider earthquakes whose fault dimensions are much less than the shortest wavelengths of seismic waves in a signal band of interest, we can regard the dislocation as occurring at a point; and we may employ the theory of Ben-Menahem et al. (1965) to calculate the relative excitation of P and S waves by a double-couple source representation. Since we are interested in the amplitude ratio of P and S waves which are recorded in the teleseismic range, we only calculate the excitation along colatitudes of the focal sphere from 140° to 165°, which is approximately the range of emergent angles for P waves associated with a surface source and recorded at distances of 20° to 90° (Appendix V, Richter, 1958). For a given fault orientation (dip and slip angles) the average displacement for the P, SV (vertically polarized), and SH (horizontally polarized) waves on this ring of the focal sphere was calculated for increments of the fault-plane dip from 0° to 90° in 10° steps for a given slip angle.

These calculations were repeated for 10° increments of the slip angle from 0° to 180°. The average P, SH, and SV excitations for each fault orientation were then themselves averaged to give an overall estimate of compressional and shear excitation for teleseismic body waves. The results were a SH/P displacement ratio of 4.8 and a SV/P ratio of 4.0. Thus considerably more shear wave energy than compressional wave energy is emitted by earthquakes, and on the average the shear energy is nearly equally divided between a horizontal and a vertical component of the S wave.

The excitation of Love and Rayleigh waves is dependent of course on the excitation of the body wave phases which are converted to these surface waves. An estimation of typical Love/Rayleigh (LQ/LR) ratios for earthquakes can be made using the point-source double-couple theory of Ben-Menahem and Harkrider (1964). Since the surface wave excitation is strongly depth dependent, we examine sources at 1, 10, and 33 km. For given dip and slip angles, the azimuth is varied from 0° to 180° in 10° steps and the average LQ/LR displacement ratio at 20 sec period is calculated for these azimuths. The calculations are repeated while changing the dip angle from 0° to 90° and the slip angle from 0° to 180°, both in 10° steps. An overall average LQ/LR for the source depth of 1, 10, or 33 km is then taken to be the mean of the average LQ/LR ratios for all the fault orientations. A Gutenberg continental earth model was used in obtaining depth-dependent parameters at a period of 20 sec for use in the radiation pattern formulas of Ben-Menahem and Harkrider. The resulting average LQ/LR ratios were 0.81 for 1 km sources, 0.84 for 10 km, and 0.87 for 33 km.

These source excitation ratios must be corrected to account for anelastic attenuation in order to obtain ratios of recorded waves at distant sites. This correction for body waves must be based on the earth's internal Q data which is only approximately known, but which is generally considered to change drastically laterally as well as vertically in the earth, and so we do not attempt to predict S/P ratios at teleseismic distances. For the surface waves, however, the attenuation of Love and Rayleigh waves is empirically nearly the same over the 15-50 second period range (Tsai and Aki, 1969); and so we expect that LQ/LR ratios measured at a distant site will not differ from the theoretical excitation ratio at the source, which we estimate to be apprcximately 0.8.

EMPIRICAL DATA ON SHEAR VERSUS COMPRESSIONAL ENERGY

Bulletins of the LRSM stations and the VELA observatories

Throughout most of the decade 1960-1970, earthquake bulletins were published by Geotech for the LRSM network and for the VELA observatories. These bulletins give ground displacement and period for all the phases identified at the various stations for earthquakes associated with USC&GS epicenters, plus data on some additional detections which could not be associated with any USC&GS epicenters. Since the bulletin data were on digital tape, we were able to survey it rapidly by computer to obtain various ratios of shear-to-compressional amplitudes (ground displacements) and thus establish a broad earthquake data base with which to compare measurements from explosions. We chose an 18-month period from June 1966 to November 1967 for the bulletin survey. Over 3,000 USC&GS events were detected by the combined LRSM-VELA network in this time period, during which there were approximately 15 to 20 LRSM stations and five VELA observatories operating. The S amplitude was taken as the largest displacement of those listed in the bulletin, regardless of the component; P and LR amplitudes were always taken from the vertical component; and LQ was taken from the horizontal components only. The unassociated phases mentioned above were ignored in the automated survey.

The results of the earthquake bulletin survey are shown in the form of histograms in Figures 1 through 5, each presenting a different ratio of shear-to-compressional amplitude (the LR phase being considered as

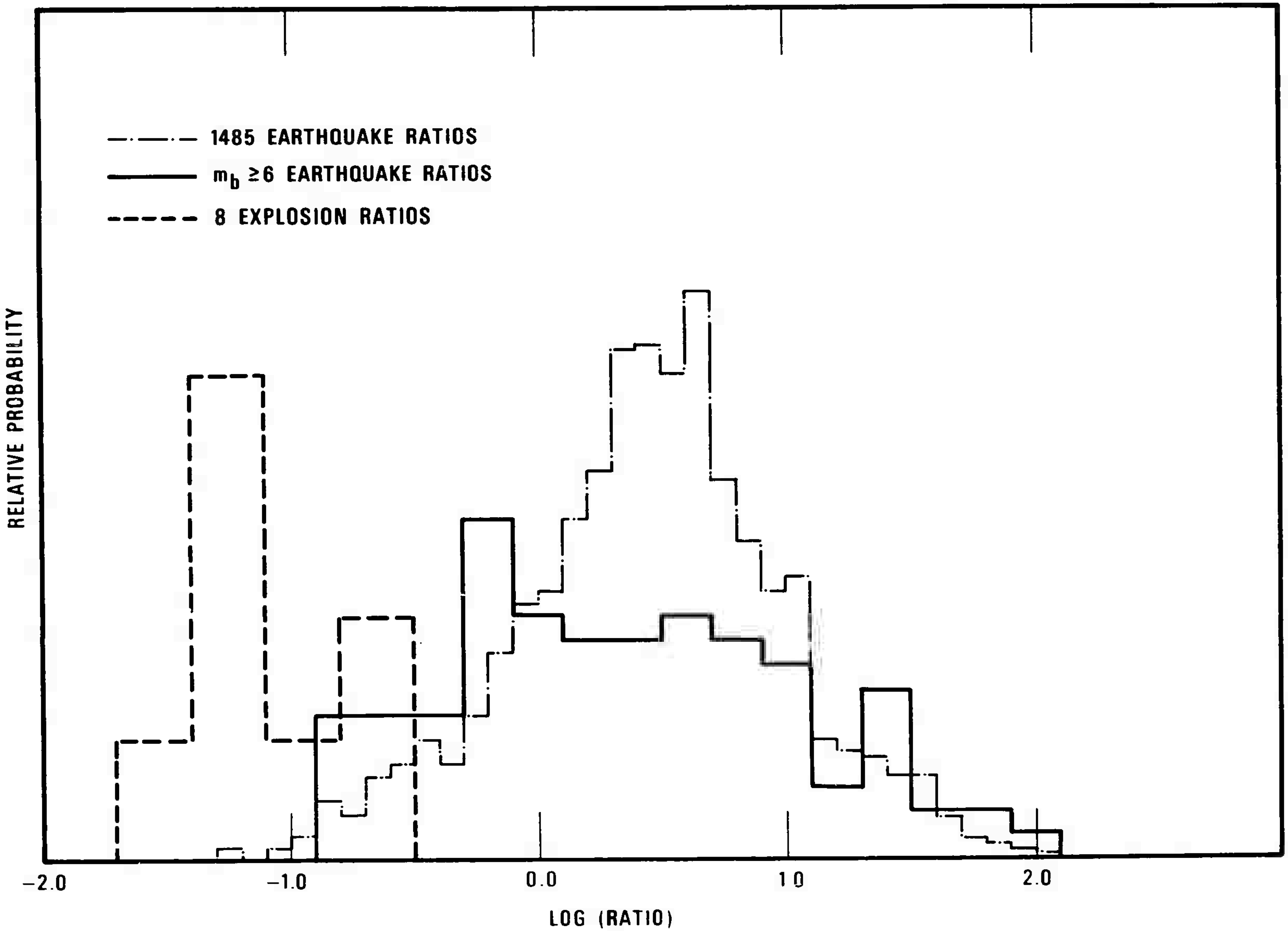

Figure 1. Ratios of short-period S to short-period P displacement for worldwide earthquakes and underground nuclear explosions in Nevada and on Amchitka Island.

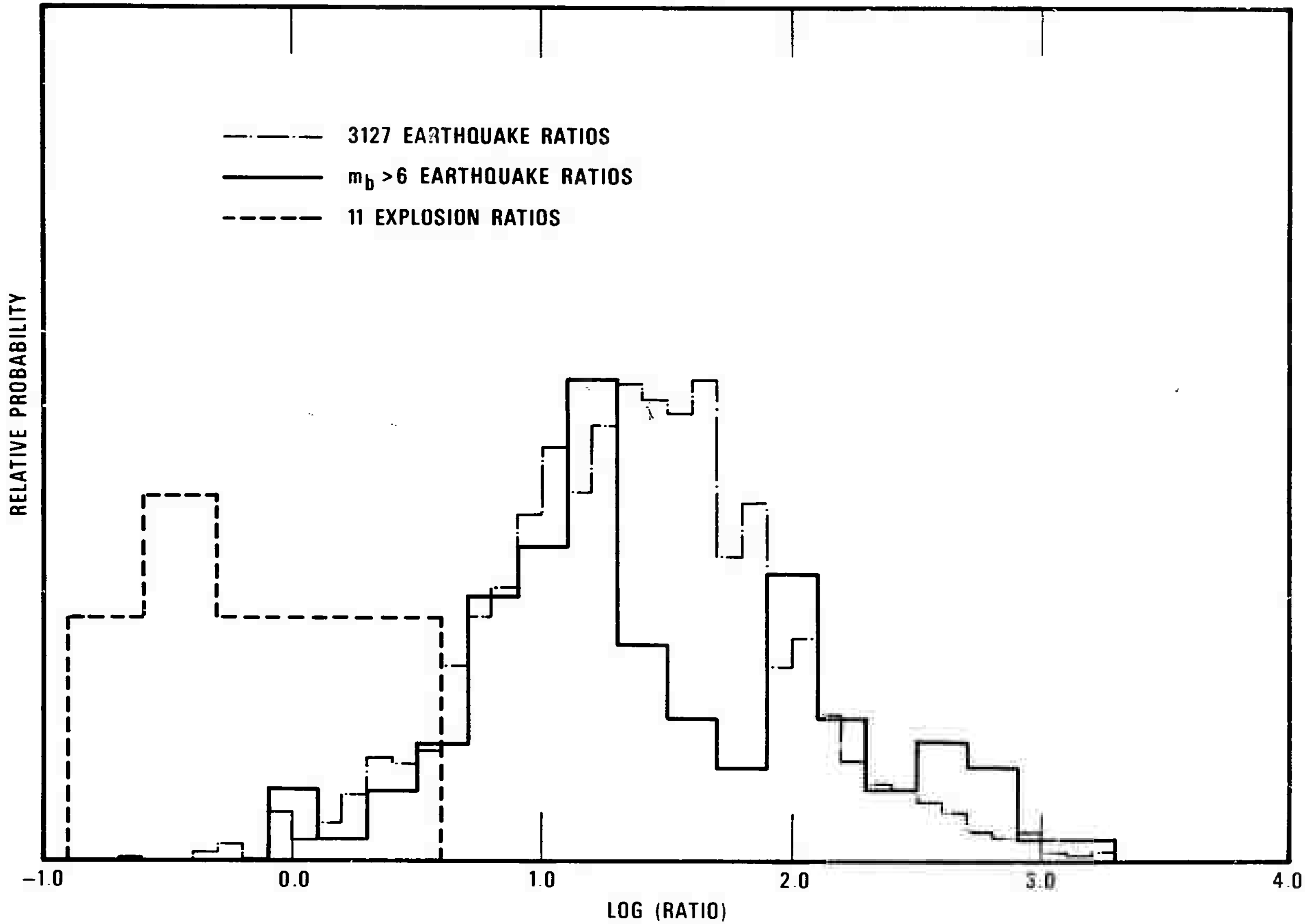

Figure 2. Ratios of long-period S to short-period P displacement for worldwide earthquakes and underground nuclear explosions in Nevada and on Amchitka Island.

compressional here). Also shown are corresponding explosion histograms, which will be discussed later.

Figures 1 and 2 show ratios with the P amplitude on the short-period recording system as the denominator. We emphasize that there is major bias in these data because the entire population of ratios is not observed; that is, there were few instances of S detection at a station without a P detection but numerous instances of the opposite case. There were actually approximately 13,000 P wave detections over the 18-month period surveyed; and, with the number of ratios summarized in Figures 1 and 2, one sees that only about one out of ten short-period P detections was followed by a short-period S detection and only about one out of four by a long-period S detection. Thus much of the population of ratios has not been sampled, and these unsampled data must have a mean to the left of the peaks of the sample distributions shown because the fact that S was not detected indicates a low S/P ratio. Reasons for the poor S detection are the higher attenuation of S waves, especially in the pass band of the short-period systems used in the LRSM-VELA network, and the presence of interfering coda at the arrival time of S waves.

In order to approximate more closely the true distribution of earthquake ratios, we selected only events with $m_b \geq 6$, for which the probability of S detection, especially short-period S, should improve considerably. Using the large events, the rate of short-period S detection was found to be approximately one for every four short-period P detections and the rate of long-period S detection was found to be one for three. Thus we still were not sampling the whole population and will still produce biased distributions, but raising the magnitude threshold further would seriously limit the amount of available data. In Figures 1 and 2 we show the resulting distributions if only the data from $m_b \geq 6$ earthquakes are used. These distributions are shifted to the left of the distributions using earthquakes of all magnitudes but still do not overlap the explosion distributions very much.

Figure 3 summarizes the S/P ratios on the long-period recordings. This distribution should have little bias because detection rates for both phases were about equal. This fact has been reported by Travis et al. (1966) for several LRSM stations using a different data base. However, the tails of the distribution may be somewhat suppressed due to noise.

Figure 4 summarizes the ratios of long-period S over Rayleigh wave amplitude. Since LR detections were more numerous in our data than the long-period S detections, the sample mean is believed to be biased to a somewhat higher value than the actual population mean. Travis et al. (1966) have reported that LR detection rates are approximately twice as great as those of long-period S for several LRSM stations.

Figure 5 presents the LQ/LR ratio distribution. Little bias exists in this distribution since the detection rates of Love and Rayleigh waves were nearly equal. As for the long-period S/P ratios, the tails of the distribution may be somewhat suppressed due to noise.

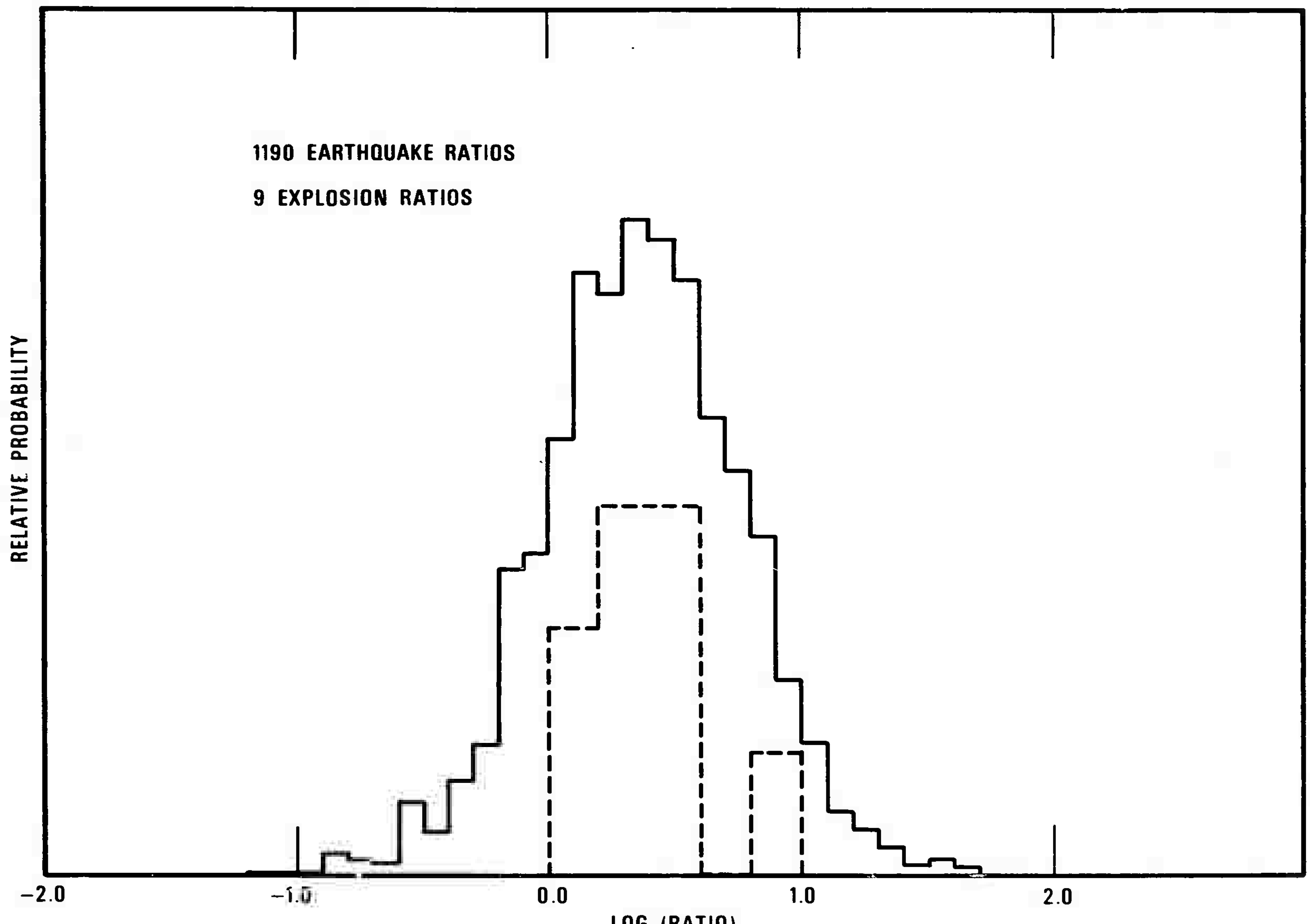

Figure 3. Ratios of long-period S to long-period P displacement for worldwide earthquakes and underground nuclear explosions in Nevada and on Amchitka Island.

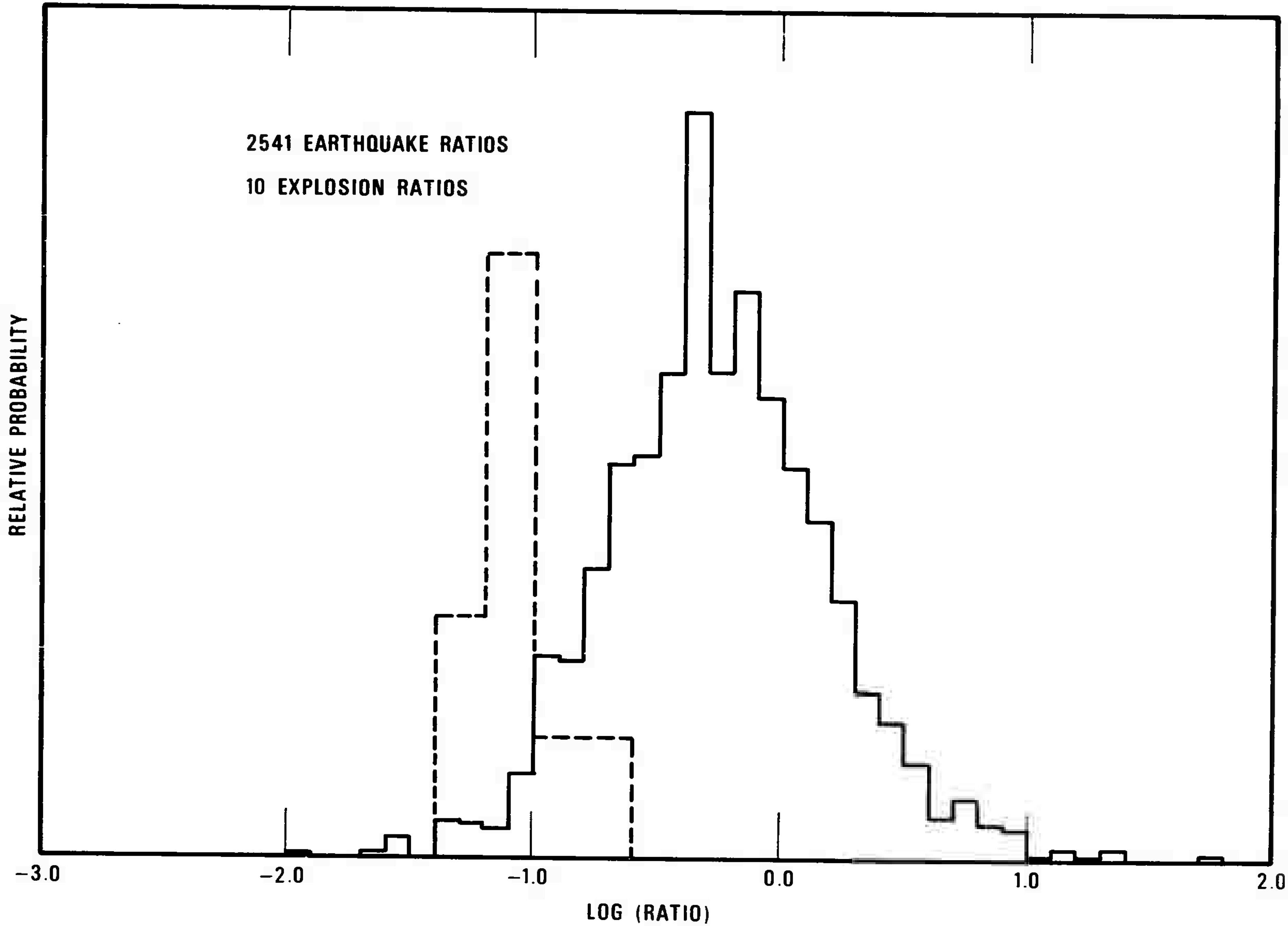

Figure 4. Ratios of long-period S to Rayleigh-wave displacement for worldwide earthquakes and underground nuclear explosions in Nevada and on Amchitka Island.

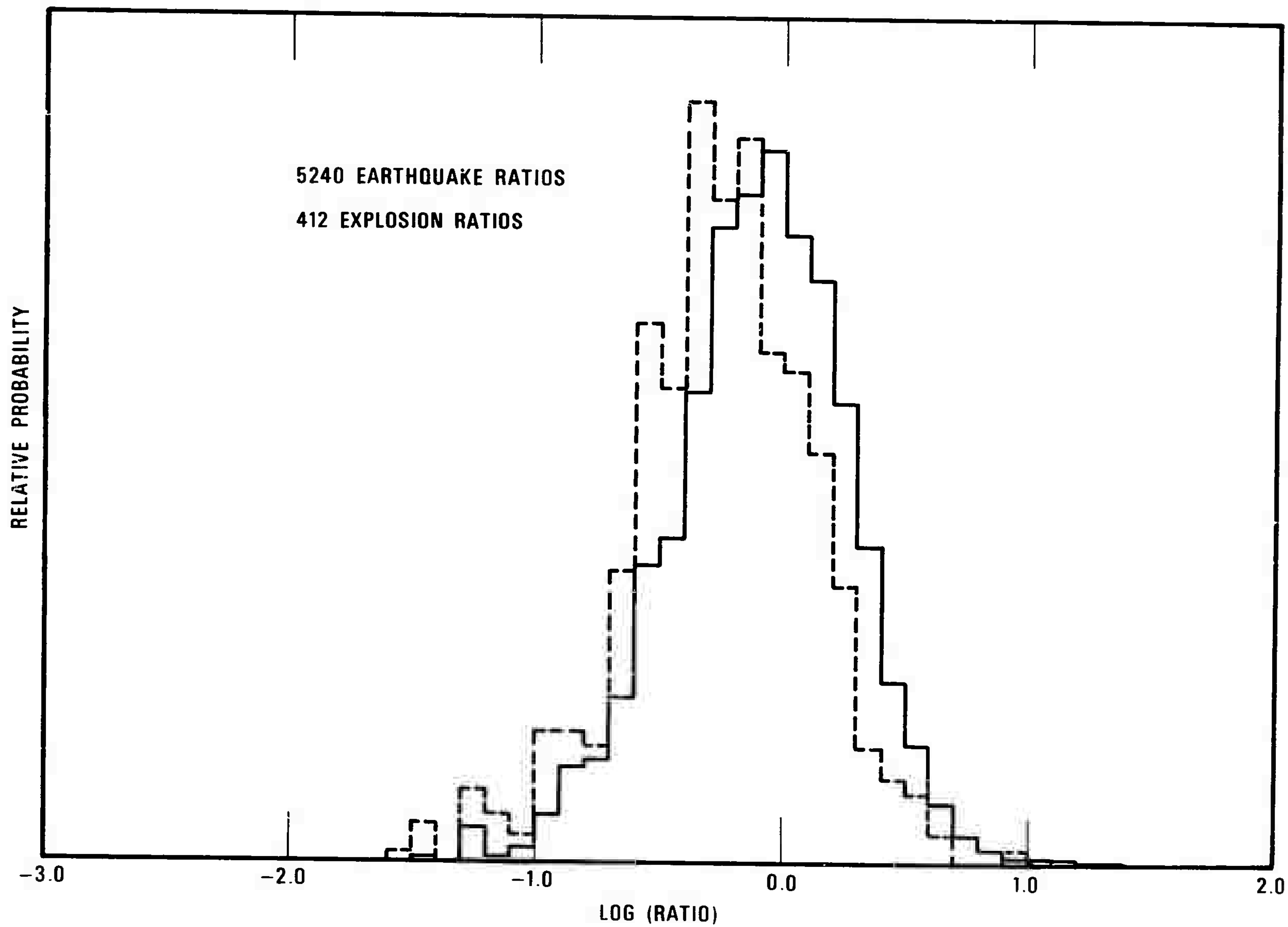

Figure 5. Ratios of Love-wave to Rayleigh-wave displacement for worldwide earthquakes and underground nuclear explosions in Nevada and on Amchitka Island.

Taking the mean LQ/LR ratio as approximately 0.9 from this sample distribution, we conclude that attenuation of Rayleigh and Love waves is nearly equal in the pass-band of the long-period recordings from the LRSM-VELA network since we have calculated the theoretical fundamental-mode LQ/LR excitation ratio for earthquakes to be approximately 0.8 in the previous section.

Analysis of NTS shots

The SDL has analyzed recordings from LRSM stations and VELA observatories for numerous underground nuclear explosions. The basic measurements for 92 United States events have been put on tape in a format similar to the earthquake bulletin data used in the last section. All but nine of the explosions were conducted at the Nevada Test Site. This data base, which we will term "Shotlist data", was then surveyed to obtain ratios of shear-to-compressional amplitudes. There was, as expected, a paucity of measurements of direct shear waves, but for the LQ phase over 400 observations were listed. In order to increase our sample of S waves and to check the validity of earlier reported picks of these waves, we reanalyzed on analog playouts the largest NTS explosions, with body-wave magnitudes of 5.5 to 6.5. Bandpass filters which we believed might enhance the S wave signal-to-noise ratio were applied; these were 0.3 to 2.0 Hz on the short-period recordings and 0.03 to 0.10 Hz on the long-period recordings. All three components were played out, but the S waves were measured on the transverse component only. This was done because an S wave on the vertical or radial component could be attributed to P-SV conversion at some boundary whereas the S wave on the horizontal should be due to shear generation by the source. Measured short-period S waves did arrive at or very near the predicted time taken from the Jeffreys-Bullen tables. It was noted that when SH was detected SV was usually of no greater amplitude and was often not visible at all. Thus we felt that there was negligible contamination of the transverse trace by SV motion slightly off azimuth. Only teleseismic stations ($\Delta > 16°$) were examined to avoid purely crustal phases or head waves from the Moho on the short-period recordings and to avoid higher-mode Love waves on the long-period recordings which arrive very close to the S wave out to 20° distance. In this reanalysis we discarded many of the Shotlist long-period S wave picks because the arrival was late and was characterized by several dispersed oscillations indicating a higher-mode Love wave. Also many Shotlist long-period S picks were not transverse S and appeared to be the vertical or radial component of the shear-coupled PL mode (Oliver, 1969). On the other hand, we feel that most of the earthquake bulletin long-period S data are valid since a cursory examination of bulletin events showed the reported S waves to be characterized by impulsive beginnings. However, even this validity may deteriorate at low S/N ratios.

Figure 1 shows the results of the analysis of short-period analog playouts from explosions. Only eight observations were considered certain. Three of them were on RK-ON recordings. This sample of S/P ratios is only a fraction of the total population since there were 165 P wave detections on the Shotlist for the 15 large shots at teleseismic distances. The distribution of the unsampled ratios is unknown, but the sample distribution probably lies somewhat to the right of the entire distribution. If we compare the earthquake and explosion distributions in Figure 1, we must keep this in mind and also the missing majority of the earthquake population. These missing data may lie somewhat to the left of the overall sample mean as indicated by the large magnitude earthquake sample.

Figure 2 shows the long-period S wave analysis results in relation to Shotlist data on short-period P waves. Only eleven S wave picks were considered to be certain: six at RK-ON, two at HN-ME, and three from MILROW recordings. The RK-ON picks may be higher-mode Love waves, but the six ratios using these picks are of the same order of magnitude as the other five ratios using arrivals believed to be purely direct shear waves. Again, as for the explosion ratios in Figure 1, we have only a fraction of the total population because only the very largest explosions produced visible long-period S waves; however, the separation is very good between earthquakes and explosions using the available data.

Figure 3 shows ratios of long-period S to long-period P. Only nine explosion ratios could be obtained from the eleven long-period shear picks because two of the MILROW stations had no visible long-period P. In any case, this very small sample indicates no difference between earthquakes and explosions in the relative excitation of long-period P and S phases.

Figure 4 presents the explosion amplitude ratios of long-period S to fundamental-mode Rayleigh. Only ten ratios were available because one station of the eleven with long-period S picks had a clipped LR phase. The limited sample shows a fair separation from the earthquake ratios.

In Figure 5 we have used the Shotlist data exclusively to get the LQ/LR ratios for explosions because we feel there can be little doubt in identifying the LQ phase. There were 712 LR measurements on the Shotlist, and only 300 did not have an associated Love wave measurement; so a total of 412 ratios were available to form the sample distribution. Since there is nearly a complete overlap between the earthquake and explosion ratios, the LQ/LR discriminant is weak even though we feel that most of the 300 unobtainable explosion ratios would fall to the left of the mean of the explosion distribution shown in Figure 5.

SHEAR DETECTION STUDIES

S-wave detection at OO-NW

An LRSM station operated for over a year in the area of the present NORSAR seismic array. This station, OO-NW, should provide an indication of the detectability of S waves at NORSAR. We selected from the NOS epicenter list all the events located on the Asian continent with magnitudes between m_b 5 and 6 for the period October 1963 through April 1965 when OO-NW was fully operational. There were 121 such events. An examination of readings at OO-NW in the LRSM Bulletins for these events revealed what appeared to be a very low percentage of both P and S detections. The film was therefore reanalyzed for all the 121 events. The short-period P wave was identified for 40 of these (several events were missed due to technical problems at the stations), the short-period S for 9 of the 40, and the long-period S for 12 of the 40. Thus we have short-period S and long-period S detection rates which are approximately 1/4 and 1/3, respectively, that for short-period P waves. Compared with the relative detection rates calculated previously for the entire LRSM-VELA network, 1/10 for short-period S waves and 1/4 for long-period S waves, these figures indicate that OO-NW, or NORSAR by inference, has a better than average detection rate for shear waves from Asian events.

S-wave detection at FB-AK

Another important LRSM site was FB-AK because it was located in the area of the present ALPA seismic array. The detectability of S waves at this site was assessed by selecting all the Asian continent events with magnitudes from m_b 5 to 6 from the NOS list of epicenters for January through September 1969 and analyzing the film for these events. LRSM bulletins were no longer being produced at this time. Of the 81 events which met the requirements, the short-period P was detected for 60, the short-period S for 24 of these 60, and the long-period S for 30 of these 60. Thus, the S wave detection rates were quite high, being approximately 1/2 that of short-period P waves in both cases. These relative rates are considerably better than for the combined LRSM-VELA network as a whole, where the rates were 1/10 and 1/4 that of short-period P for short-period and long-period S, respectively.

DISCUSSION

Of the five histograms showing the distribution of various shear-to-compressional displacement ratios, only short-period S over short-period P, long-period S over short-period P, and long-period S over Rayleigh indicate significant separations between earthquake and explosion samples. A serious but unavoidable deficiency in these plots is the absence of ratios for most of the total population due to background noise on the seismograms. There is only one safe manner in which to employ this type of limited information in discrimination; that is, to regard S/P ratios that lie to the right of the present explosion population to be earthquake generated with high probability. Low S/P ratios within the explosion populations cannot be considered as explosion generated with high probability simply because the true earthquake distribution in the region is unknown. Furthermore, explosion identification based on the lack of visible S waves, whereby a noise measurement defines the upper bound of the S/P ratio, will be unreliable for the same reason.

Application of an S wave discriminant depends then on greatly improving the signal-to-noise ratio for this arrival in both the long-period and short-period bands. Array methods for accomplishing this have received no attention except for the report by De Noyer (1966) on the use of a four-element short-period array. Improvement can also be obtained by a combination of pendulum and strain seismographs (Der, 1972). The importance of good sites cannot be overemphasized because anelastic attenuation is highly variable, especially with the short-period S. Our data show that RK-ON is a good site for detecting S from NTS explosions. We also showed that a single sensor at the NORSAR and ALPA arrays should be a better S-wave detector than a typical station in the LRSM-VELA network. However, this last result should be tempered by the liklihood that the LRSM-VELA bulletin S detections were considerably fewer than possible due to the manner of analysis. The analysis of the recordings was done without epicenter information and was therefore an impaired method which would miss many phases with low signal-to-noise ratios.

For teleseismic S waves we have found over an order of magnitude difference in shear generation between earthquakes and explosions of equivalent m_b. Earlier work on regional S waves and L_g waves has shown much less separation (Press et al. 1963; Booker and Mitronovas, 1964; Lambert, 1972). The explanation may lie in the difference in ray paths to regional and teleseismic stations. Raypaths to regional stations are through the crust where inhomogeneous structure facilitates conversion of P, SV, or LR waves to horizontal shear modes. The Lg phase itself can be explained by continuous conversion of short-period fundamental and higher-mode LR to similar LQ waves along the path. In contrast, ray paths to teleseismic stations will traverse structure which has fewer and less severe velocity gradients and is therefore less likely to cause mode conversion.

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