

PL-TR-96-2251

**IMPROVED UNDERSTANDING OF BROADBAND  
Lg/P RATIO AND ITS APPLICATION TO  
DISCRIMINATING EARTHQUAKES FROM  
EXPLOSIONS, INCLUDING DECOUPLED SHOTS**

**Indra N. Gupta**

**Multimax, Inc.  
1441 McCormick Drive  
Largo, MD 20774**

**26 September 1996**

**Scientific Report No. 1**

**DTIC QUALITY INSPECTED 2**

**Approved for public release; distribution unlimited.**



**DEPARTMENT OF ENERGY  
Office of Non-Proliferation  
and National Security  
WASHINGTON, DC 20585**

**19970206 107**



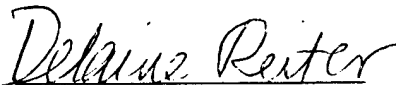
**PHILLIPS LABORATORY  
Directorate of Geophysics  
AIR FORCE MATERIEL COMMAND  
HANSCOM AFB, MA 01731-3010**

SPONSORED BY  
Department of Energy  
Office of Non-Proliferation and National Security

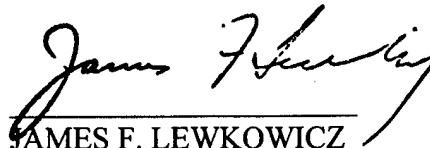
MONITORED BY  
Phillips Laboratory  
CONTRACT No. F19628-95-C-0176

The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either express or implied, of the Air Force or U.S. Government.

This technical report has been reviewed and is approved for publication.



DELAINE REITER  
Contract Manager  
Earth Sciences Division



JAMES F. LEWKOWICZ  
Director  
Earth Sciences Division

This report has been reviewed by the ESD Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS).

Qualified requestors may obtain copies from the Defense Technical Information Center. All others should apply to the National Technical Information Service.

If your address has changed, or you wish to be removed from the mailing list, or if the addressee is no longer employed by your organization, please notify PL/IM, 29 Randolph Road, Hanscom AFB, MA 01731-3010. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document requires that it be returned.

# REPORT DOCUMENTATION PAGE

*Form Approved*  
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Avenue Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project(0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE <b>26 September 1996</b>	3. REPORT TYPE AND DATES COVERED <b>Scientific No. 1</b>	
4. TITLE AND SUBTITLE <b>Improved Understanding of Broadband Lg/P Ratio and Its Application to Discriminating Earthquakes from Explosions, Including Decoupled Shots</b>		5. FUNDING NUMBERS <b>PE 69120H PR DENN TA GM WU AP F19628-95-C-0176</b>	
6. AUTHOR(S) <b>Indra N. Gupta</b>		8. PERFORMING ORGANIZATION REPORT NUMBER <b>MM-02-96-001</b>	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Multimax, Inc. 1441 McCormick Drive Largo, MD 20774</b>		10. SPONSORING / MONITORING AGENCY REPORT NUMBER <b>PL-TR-96-2251</b>	
9. SPONSORING / MONITORING AGENCY NAMES(S) AND ADDRESS(ES) <b>Phillips Laboratory 29 Randolph Road Hanscom AFB, MA 01731-3010 Contract Manager: Delaine Reiter / GPE</b>		11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION / AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>		12b. DISTRIBUTION CODE	
13. ABSTRACT ( <i>Maximum 200 words</i> )  An understanding of the mechanism of generation of Lg from underground nuclear explosions is essential for seismic monitoring and source discrimination. Near-source scattering of explosion-generated Rg into S appears to be responsible for the low-frequency Lg from nuclear explosions at both NTS and Kazakh test sites. The source of Rg has a strong compensated linear vector dipole (CLVD) component, and the prominent low-frequency null in the observed Lg is due to Rg from a CLVD source. In this study, the dependence of spectral nulls on source parameters is first investigated by analyzing Lg from a large number of NTS explosions. Most Lg spectra indicate prominent nulls at frequencies which vary with shot depth and are in remarkably good agreement with those expected from Rg due to a CLVD source at about one-third the shot depth. Analysis of low-frequency Lg from explosions at Kazakh, Lop Nor, and Azgir test sites also show that the observed spectral nulls depend strongly on shot depth and local velocity structure, and a comparison with theory provides useful source information, including accurate shot depth. By providing an improved understanding of Lg and its usefulness for obtaining source information, these results make an important contribution to seismic monitoring of the Comprehensive Test Ban Treaty.			
14. SUBJECT TERMS <b>Lg, regional phases, scattering of Rg, source discrimination, seismic monitoring, NTS, Kazakh, Lop Nor, CTBT</b>		15. NUMBER OF PAGES <b>36</b>	
17. SECURITY CLASSIFICATION <b>UNCLASSIFIED</b>		16. PRICE CODE	
18. SECURITY CLASSIFICATION OF THIS PAGE <b>UNCLASSIFIED</b>	19. SECURITY CLASSIFICATION OF THIS PAGE <b>UNCLASSIFIED</b>	20. LIMITATION OF ABSTRACT <b>UNCLASSIFIED</b>	



## CONTENTS

INTRODUCTION .....	1
ANALYSIS OF LOCAL AND REGIONAL DATA FROM NTS SHOTS .....	1
SPECTRAL NULLS IN L <sub>g</sub> FROM KAZAKH EXPLOSIONS .....	14
CHINESE TESTS AT LOP NOR .....	14
AZGIR PNE AT ILPA ARRAY .....	19
DISCUSSION AND CONCLUSIONS .....	19
REFERENCES .....	23
ACKNOWLEDGMENTS .....	24



## SUMMARY

This annual report deals with a study of the low frequency Lg from explosions at the Nevada, Kazakh, Lop Nor, and Azgir Test Sites. An understanding of the mechanism of generation of Lg from underground nuclear explosions is essential for seismic monitoring and source discrimination at regional distances. Earlier studies have suggested that near-source scattering of explosion-generated Rg into S is responsible for the low-frequency Lg from nuclear explosions at both NTS and Kazakh test sites. A recent analysis of regional data from NTS explosions has indicated that the source of Rg waves must have a strong compensated linear vector dipole (CLVD) component and the prominent low-frequency spectral null in the observed Lg is due to Rg from a CLVD source. An objective of this research is to investigate the spectral nulls and other characteristics of the low-frequency Lg from explosions at various test sites so that the scattering mechanism and its potential for obtaining useful source information can be fully exploited. The dependence of spectral nulls on shot depths and other source parameters is first investigated by analyzing Lg from a large number of Yucca Flats (NTS) explosions, with known ground truth, recorded at several broadband stations. Methods of analysis include narrow bandpass filtering, network-averaging, spectral ratios, and comparison of results with those from synthetics. Most Lg spectra indicate prominent nulls at frequencies which appear to vary systematically with shot depth and are in remarkably good agreement with those expected from Rg due to a CLVD source at about one-third the shot depth.

Low-frequency Lg from nuclear explosions at Kazakh, Lop Nor, and Azgir test sites are analyzed by using regional data from mostly broadband and a few other (short-period and long-period) stations, including WMQ and stations belonging to the NRDC, KNET and the ILPA array. The observed spectral nulls, although generally not as strong as for the NTS shots, are in most cases distinct and identifiable. The null frequencies appear to depend strongly on shot depth and local velocity structure and a comparison with theory provides useful source information, including shot depth with an accuracy not possible by other methods. An effective CLVD source is present not only for Lg from NTS explosions but also for explosions from other test sites in significantly different geological environments. By providing an improved understanding of Lg from explosions and its usefulness for obtaining source information, these results make important contribution to seismic monitoring of the Comprehensive Test Ban Treaty.



## INTRODUCTION

A clear understanding of the broadband characteristics of regional phases and their dependence on various near-source parameters must be obtained if successful seismic monitoring techniques developed in one region are to be used in other locations. Lg is often the largest seismic phase from both explosion and earthquake sources recorded at regional distances. Numerous studies have demonstrated the usefulness of Lg for detection, source discrimination, and yield estimation of underground nuclear explosions. However, a full understanding of the generation and spectral characteristics of Lg, essential for providing confidence in our ability to monitor nuclear test ban treaties, is largely lacking. Perhaps the most enigmatic aspect of Lg from explosions is their spectra's relative richness in low frequency energy compared to earthquake Lg spectra. Gupta *et al.* (1991, 1992) proposed a theoretical model suggesting that the near-source scattering of explosion-generated Rg into S makes a significant contribution to the low-frequency Lg. This mechanism explains why the low-frequency Lg from explosions is so large that it destroys the discrimination capability of Pn/Lg amplitude ratios at frequency of about 1 Hz. Most evidence for this hypothesis came from analysis of regional data from nuclear explosions at both Nevada and East Kazakh test sites. Independent support for this mechanism also came from an examination of the source spectra of Lg from East Kazakh and Novaya Zemlya explosions by Israelsson (1992), and from analysis of Lg spectral ratios from Yucca Flats (NTS) explosions by Patton and Taylor (1995).

In order to explain pronounced spectral nulls in the Lg spectra of several Yucca Flats (NTS) explosions, Patton and Taylor (1995) suggested that the Rg waves must originate mainly from a compensated linear vector dipole (CLVD) source and the prominent low-frequency null is due to an excitation null in Rg for a buried CLVD source. It follows that an analysis of the low-frequency Lg may be useful for estimating source depth if one can establish a relationship between the centroid depth of the CLVD source and the explosion depth. Modeling of the observed Lg with the help of synthetics may also provide other source and near-source information. Rg is stronger for shallow sources such as mining explosions and rockbursts than for deeper sources such as earthquakes. The main objective of this research is to investigate broadband characteristics of regional phases, especially Lg, under various tectonic settings. The results contribute to monitoring of a CTBT by providing a physical basis for regional discriminants, essential for improving their reliability and transportability from one region to another.

## ANALYSIS OF LOCAL AND REGIONAL DATA FROM NTS SHOTS

A comprehensive study of the generation of Lg from underground nuclear explosions and its dependence on source and near-source parameters requires analysis of large amounts of data for which detailed ground truth information is available. This is mostly true of only the NTS explosions although limited source information is now available for several Kazakh Test Site (KTS) explosions. Therefore, we first investigated regional and other data from NTS shots (Gupta and Zhang, 1996).

The time-varying spectral characteristics of the observed seismic arrivals are examined by using narrow bandpass filtering (NBF) which provides amplitudes for various values of group velocity and period. The NBF technique, described in detail by Seneff (1978), has been employed by several investigators (*e.g.* Kafka, 1990) to study Rg from shallow sources. The group velocity curves are computed by using a moving zero-phase Gaussian filter. The period axis represents the central period of the filter and the velocity axis is simply epicentral distance/travel-time. The filter is applied at each period, the energy envelope computed, and the energy envelope curves are represented in the form of a two-dimensional matrix which is contoured.

Digital, broadband data from several NTS explosions recorded at both local and regional distances are available from Los Alamos National Laboratory (Edwards and Baker, 1993; Taylor, 1993). NBF analysis was first carried out on local data from the nuclear explosion, Metropolis (10 March 1990,  $m_b = 5.0$ , depth 469 m) at several recording stations, covering the distance range of 114 to 274 km (Edwards and Baker, 1993). Figure 1 shows locations of Metropolis, field deployment stations DM, MV, LM, and HD at local and near-regional distances (Edwards and Baker, 1993), Sandia National Lab (SNL) stations TON, DRW, NLS, and LDS, and Lawrence Livermore National Lab (LLNL) stations ELK, MNV, LAC, and KNB. Using the vertical component data from the intermediate-period system (which records velocity at frequencies above the seismometer period of 5 sec), results from four stations are shown in Figure 2. At the three short distances (Figures 2a, b, c), the direct fundamental-mode Rayleigh (which includes the short period Rg) are well recorded but the NBF results show sharp drop in amplitude for the shorter periods. A possible explanation is that, within a few km of the source, the shorter period Rg is scattered into S waves which travel with a velocity considerably higher than velocity of the shorter-period Rg. A spectral null at period of about 1.7 sec is observed in energy traveling with velocity of about 1 to 4 km/sec, which includes not only Rg but also S-wave group arrivals such as Sg, Lg and Sn. At larger distance (Figure 2d), the spectral null is clearly observed in Lg which has become the dominant phase because of greater attenuation with distance of Rg. The spectral null in the Rg-S wave group at shorter distances also appears in Lg at regional distances, indicating that the Rg spectrum is imprinted onto the scattered S waves. These results strongly support importance of the CLVD source and the near-source scattering of explosion-generated Rg into S waves and subsequently into Lg.

We also analyzed regional data from stations that recorded, in addition to Metropolis, two more Yucca Flats explosions, Texarkana (10 February 1989,  $m_b = 5.2$ , depth 503 m) and Tulia (26 May 1989,  $m_b = 3.7$ , depth 396 m), separated by about 5 km (Figure 3). NBF analyses of the vertical component, long-period data, with peak response at slightly less than 0.1 Hz (Taylor, 1993) from station TON are shown in Figure 4. Prominent spectral nulls in the S-wave group or Lg, with velocity of about 3 km/sec, are observed at periods of 1.5 and 1.3 sec for Texarkana and Tulia, respectively. NBF of Tulia recorded at DM also suggests a null at period of about 1.3 sec. The observed difference in null period for Texarkana and Tulia are likely to be due to several factors such as differences in their shot depths, medium velocities, and yield.

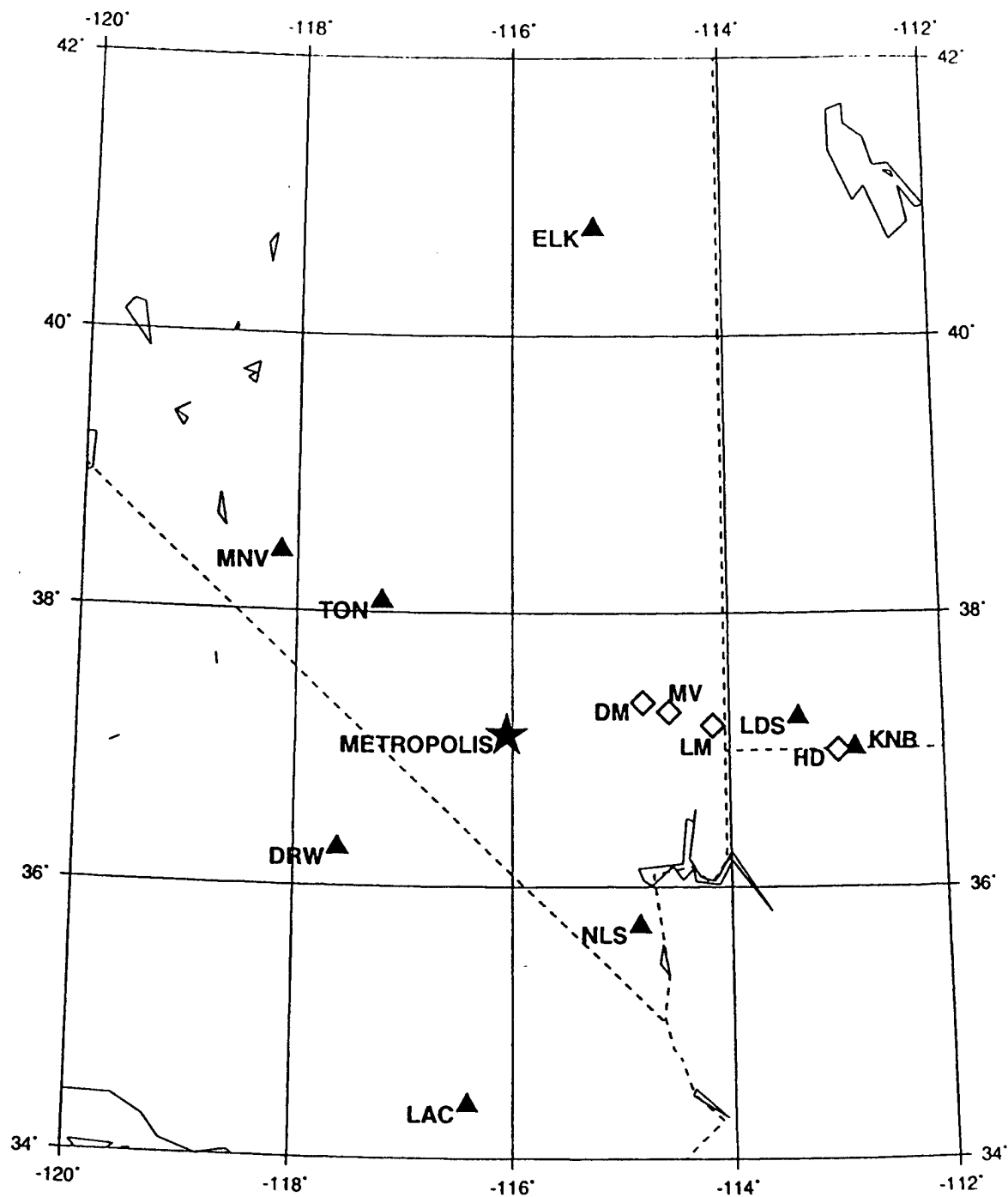


Figure 1. Location map of the underground explosion, Metropolis and local and regional stations providing data used in this study. Stations MNV, KNB, LAC, and ELK belong to the LLNL network and TON, DRW, NLS, and LDS are part of the SNL network.

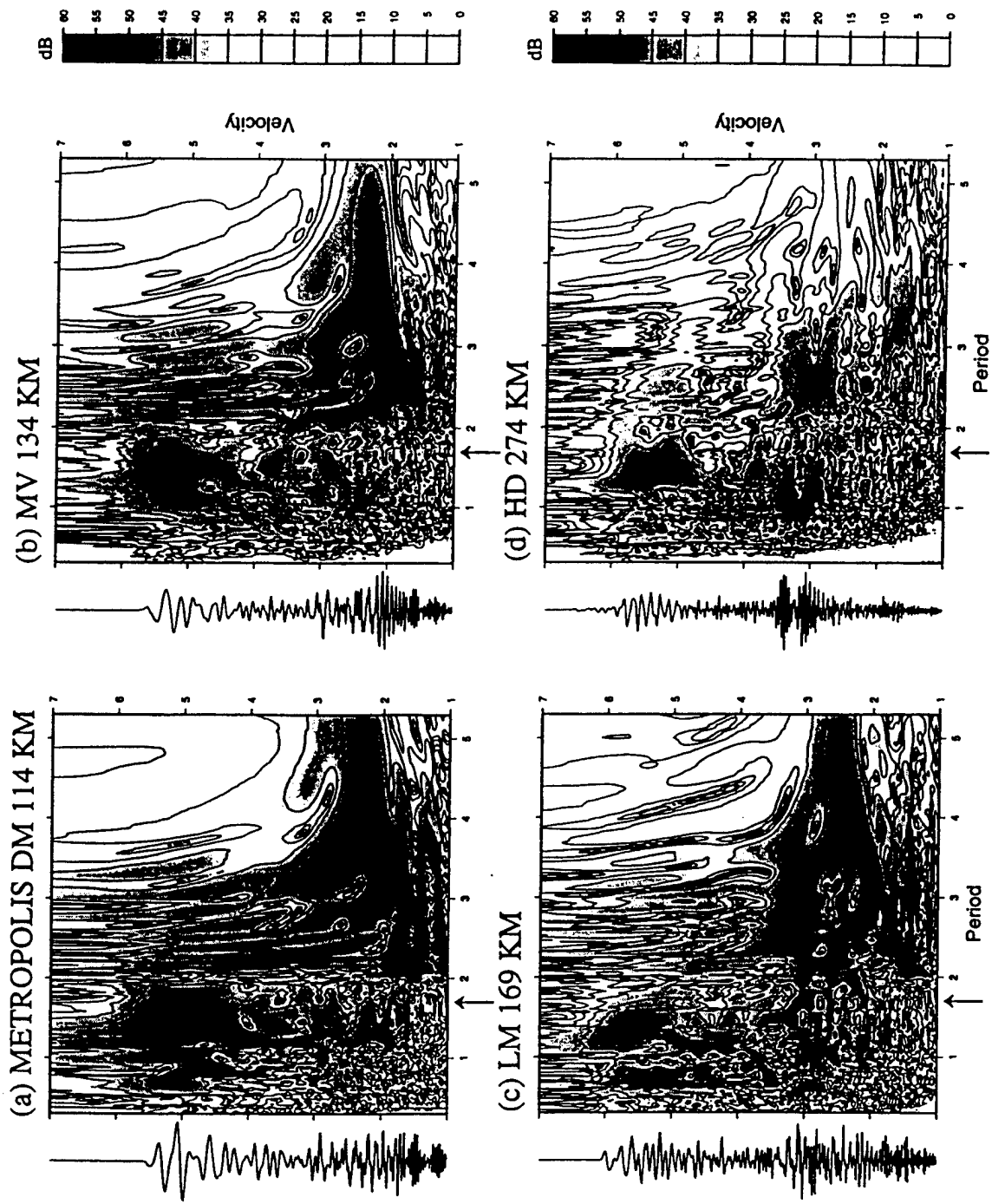


Figure 2. Narrow bandpass filtered records of Metropolis at four different distances indicating progressive (with distance) scattering of Rg into Lg and spectral null at period of 1.7 sec in both Rg and Lg.

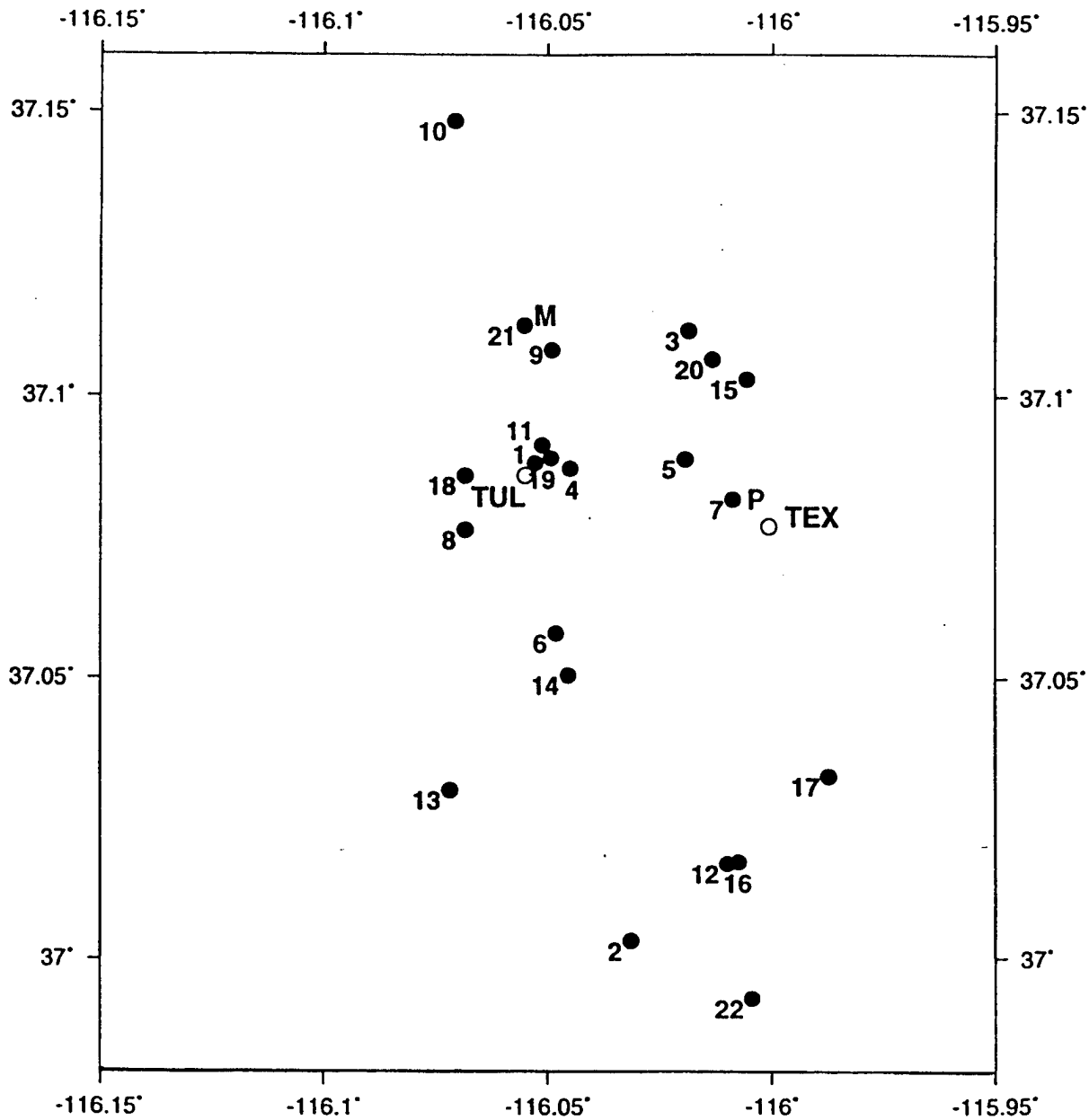


Figure 3. Location map of 22 underground explosions used in this study, including Metropolis and Paliza, denoted by M and P, respectively, with numbers corresponding to those in Table 1. Locations of two additional shots Texarkana and Tulia (denoted by TEX and TUL, respectively), are also shown.

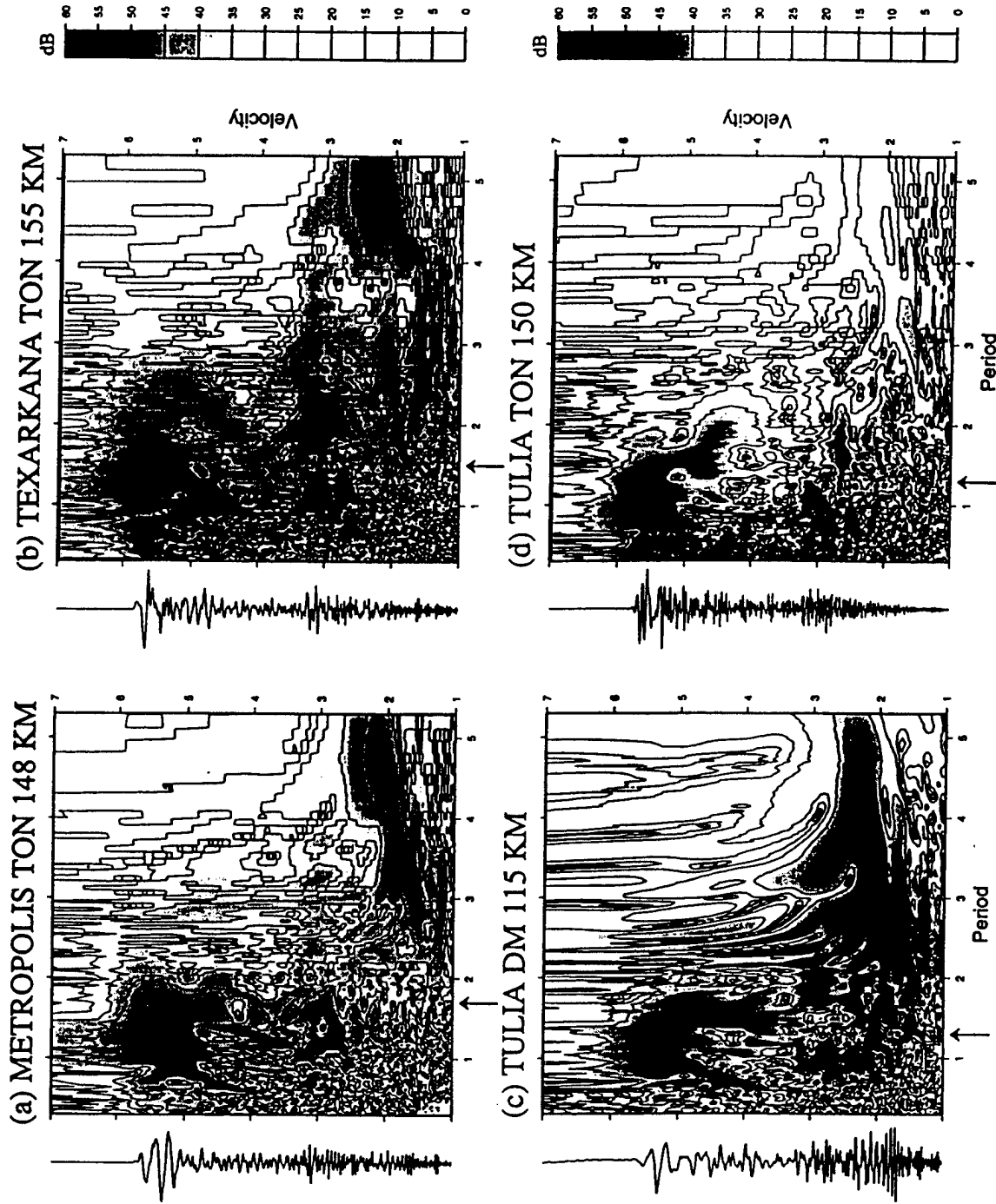


Figure 4. Similar to Figure 2 for the nuclear explosions Metropolis, Texarkana, and Tulia with shot depths 469, 503, and 396, respectively. The spectral nulls appear to vary with both shot depth and subsurface structure.

The dependence of spectral nulls on shot depths is investigated by analyzing Lg from 22 Yucca Flats explosions (Table 1 and Figure 3) recorded well at the four broadband stations (MNV, KNB, LAC, and ELK) of the LLNL network. Table 1 includes the overburden velocity (average compressional-wave velocity between the shot point and the surface measured by sonic logs) which suggests considerable lateral variation. Using 51.2 sec long Lg windows, multitapered spectra were obtained for each of the four stations and corrected for attenuation by using Lg(Q) values in Patton (1988). Network-averaged spectra were also obtained by averaging (on log scale) the four single-station spectra. As an example, results for Metropolis are shown in Figure 5 which indicates distinct nulls at each of the four stations. The average null frequency at about 0.68 Hz appears stable since the null frequencies show only a small variation from one station to another. Similar results based on use of the four SNL stations are shown in Figure 6 which again shows distinct nulls at each station and the average null frequency is again 0.68 Hz. The consistency of spectral nulls in Figures 5 and 6 rules out the possibility of these nulls owing their origin to factors such as site effects or multipathing.

Results from 8 shots, arranged in order of decreasing shot depth and recorded at MNV, are shown in Figure 7a whereas the LLNL network-averaged spectra are shown in Figure 7b. As expected, spectral nulls in the network-averaged spectra are considerably more distinct and reliable than those from a single station. The network-averaged spectra were used to determine the spectral null frequencies (included in Table 1). Both Figures 7a and 7b indicate an increase in the null frequency with decreasing shot depth but the increase in null frequency is at first small and much larger for shallower depths. It should be noted that the null frequencies in Table 1 also indicate some regional variation for shots with nearly the same shot depth. For example, the individual and average spectra for Paliza (Figure 8) show a spectral null at about 0.78 Hz whereas those for Metropolis, with shot depth differing by only 3 m, have a spectral null at 0.68 Hz (Figures 5 and 6). The main reason for this variation is probably the presence of significant lateral variation in the subsurface as also evidenced by the large (1.3 to 1.8 km/sec) variation in the overburden velocities (Table 1).

# METROPOLIS (DEPTH 469 m), LLNL STATIONS

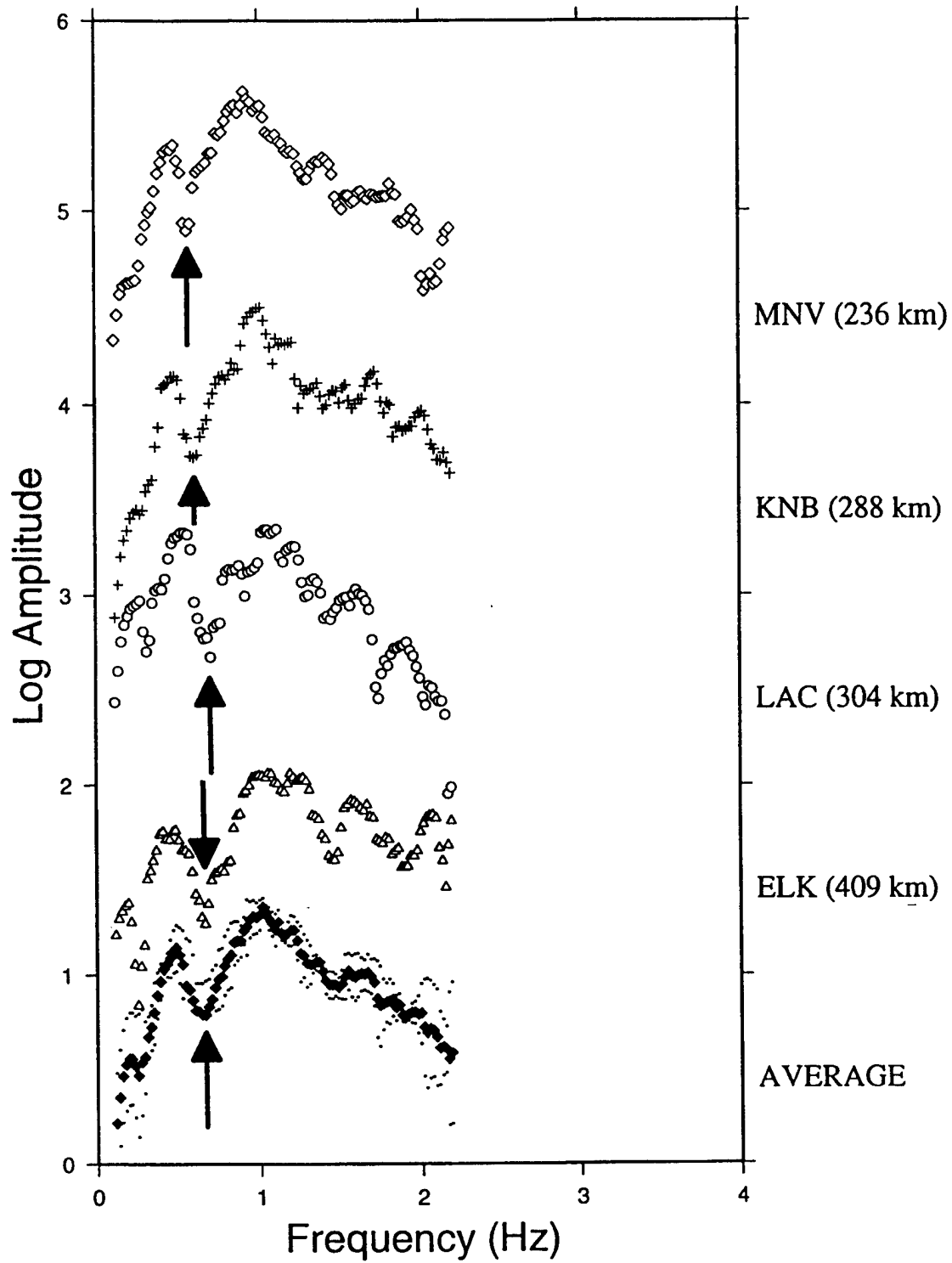


Figure 5. Single station and network-averaged Lg spectra, based on LLNL stations, for Metropolis, indicating a spectral null at frequency of about 0.7 Hz.

# METROPOLIS (DEPTH 469 m), SNL STATIONS

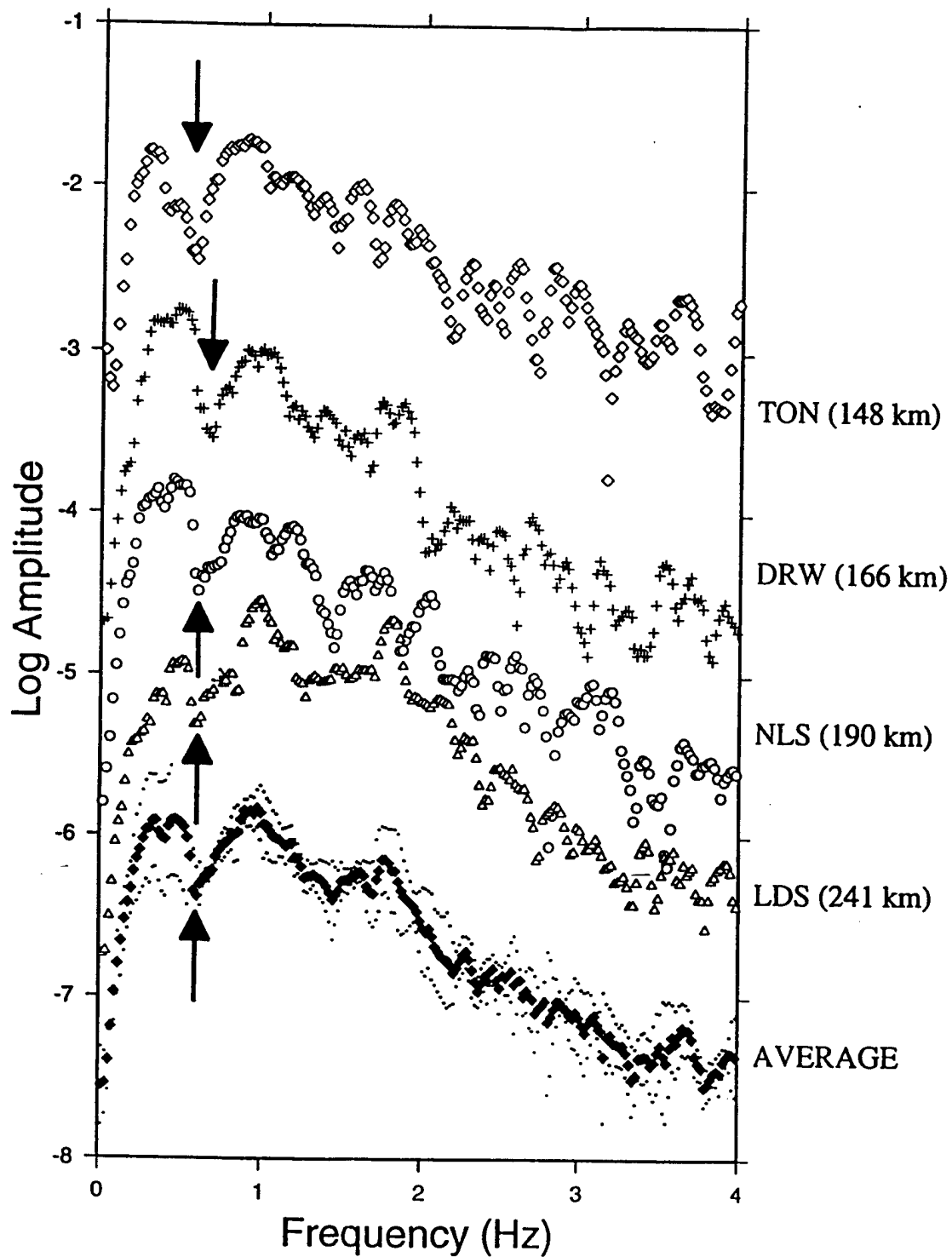


Figure 6. Single station and network-averaged Lg spectra, based on SNL stations, for Metropolis, again indicating a spectral null at frequency of about 0.7 Hz

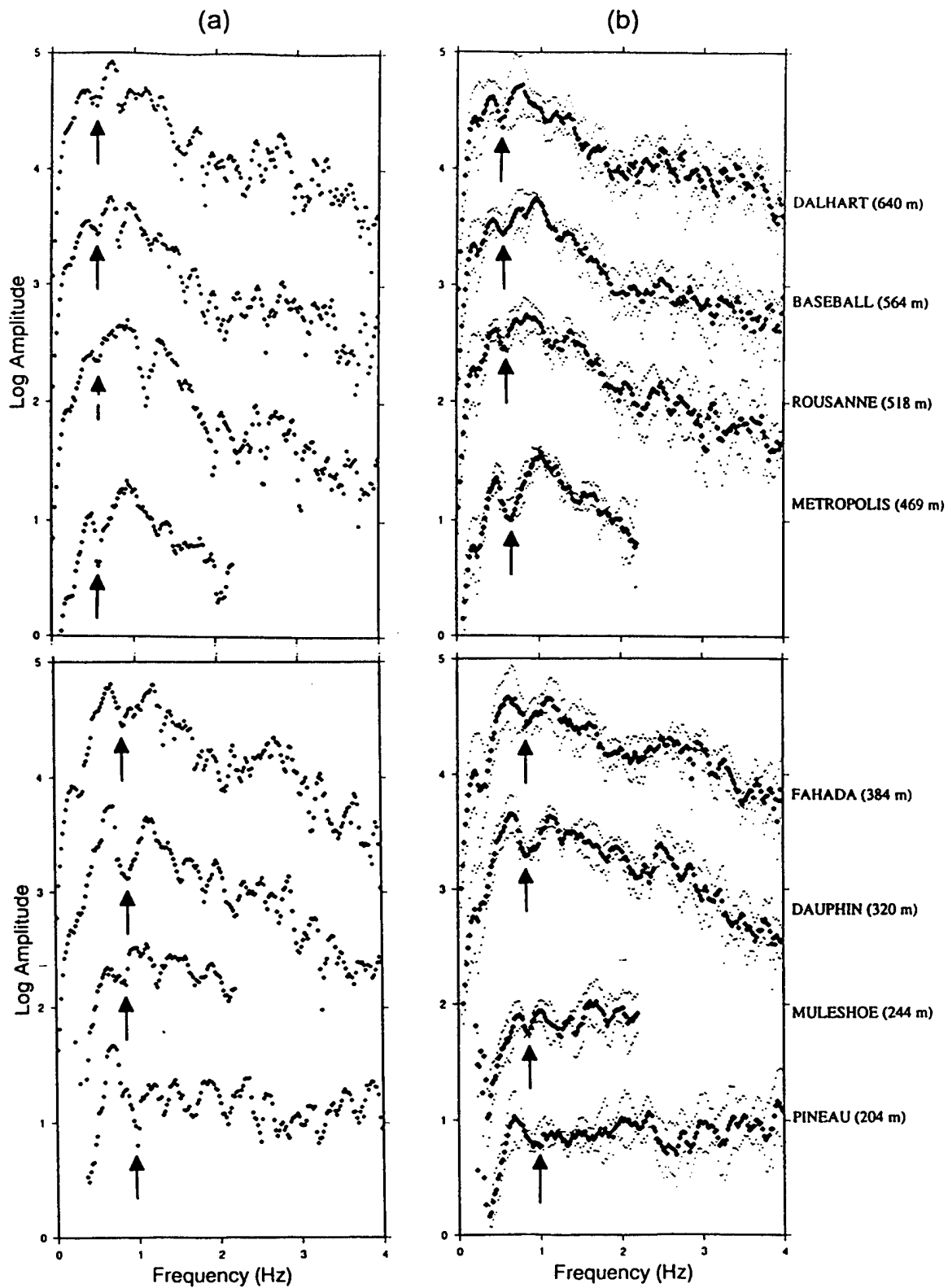


Figure 7. Spectra of Lg for 8 explosions at Yucca Flats with shot depths as indicated, based on (a) data from a single station, MNV, and (b) network averaged over all four LLNL stations, showing systematic variation of spectral null frequency (indicated by arrows) with shot depth.

PALIZA (DEPTH 472 m), LLNL STATIONS

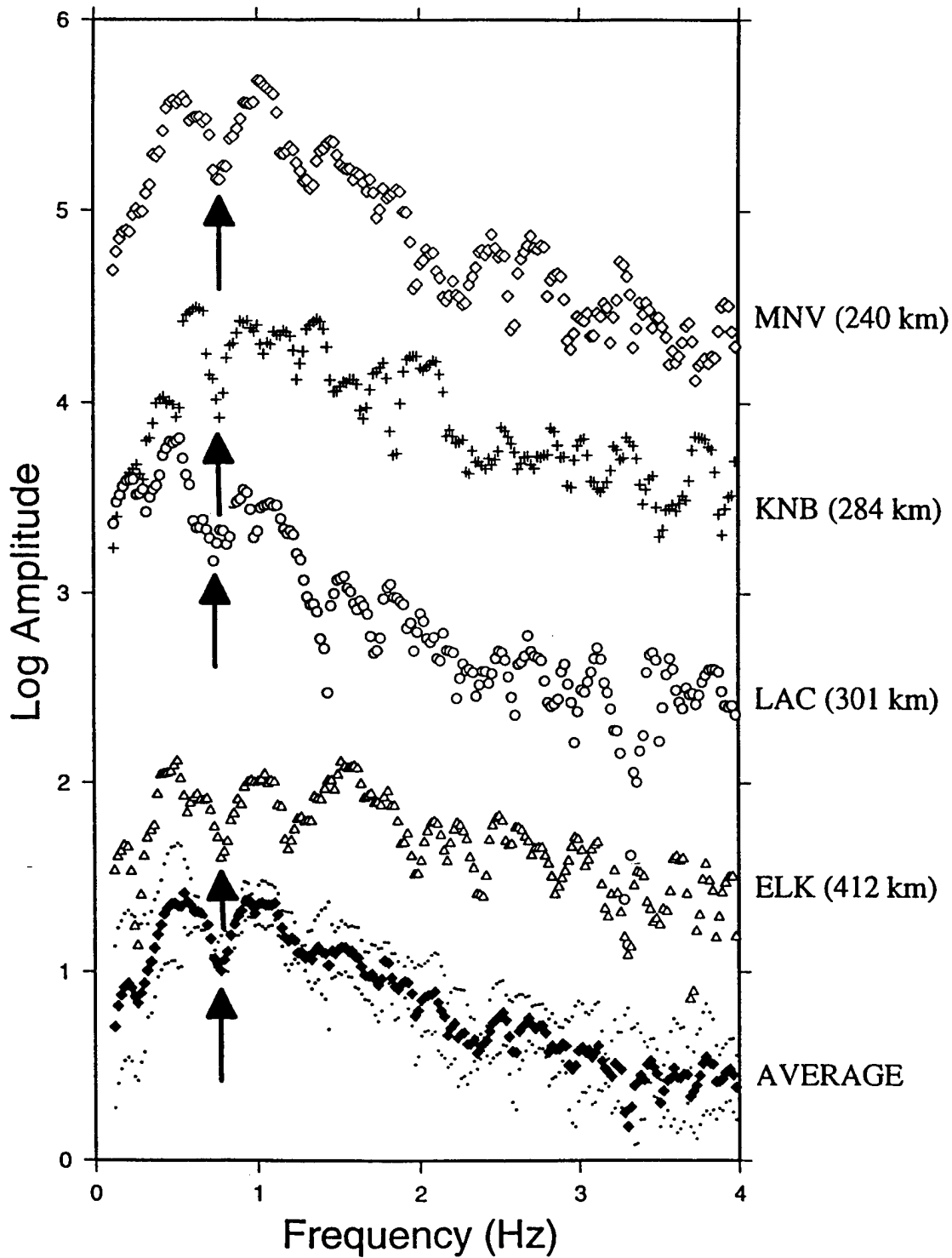


Figure 8. Single station and network-averaged Lg spectra, based on LLNL stations, for Paliza, indicating a spectral null at frequency of about 0.8 Hz.

Table 1: Yucca Flats Explosions and Associated Lg Null Frequencies

No	Date	Name	Depth (m)	Velocity (km/sec)	Frequency (Hz)
1	06 Sep 79	HEARTS	640	1.763	0.55
2	22 May 80	FLORA	335	1.257	0.85
3	14 Nov 80	DAUPHIN	320	1.420	0.82
4	15 Jan 81	BASEBALL	564	1.970	0.55
5	16 Jul 81	PINEAU	204	1.125	1.00
6	04 Sep 81	TREBBIANO	305	1.465	0.80
7	01 Oct 81	PALIZA	472	1.497	0.78
8	11 Nov 81	TILCI	445	1.600	0.80
9	12 Nov 81	ROUSANNE	518	1.580	0.60
10	03 Dec 81	AKAVI	494	1.730	0.82
11	28 Jan 82	JORNADA	640	1.695	0.53
12	17 Apr 82	TENAJA	357	1.310	0.86
13	10 Dec 82	MANTECA	413	1.610	0.90
14	11 Feb 83	COALORA	274	1.340	0.82
15	26 May 83	FAHADA	384	1.500	0.82
16	02 Aug 84	CORREO	335	1.305	0.84
17	21 May 88	LAREDO	350	1.600	0.91
18	30 Aug 88	BULLFROG	489	1.622	0.80
19	13 Oct 88	DALHART	640	1.770	0.56
20	15 Nov 89	MULESHOE	244	1.330	0.87
21	10 Mar 90	METROPOLIS	469	1.515	0.68
22	21 Jun 90	AUSTIN	351	1.370	0.85

For a homogeneous semi-infinite medium, one can determine (e.g. Aki and Richards, 1980) that the CLVD spectral null frequency occurs approximately at  $V/(16h)$  where  $V$  is the P-wave velocity and  $h$  is depth of the CLVD source (Poisson's ratio of 0.25 is assumed). This means that the null frequency is inversely proportional to source depth and directly proportional to medium velocity. In order to understand the observed variation with depth of the Yucca Flats explosions, the wavenumber integration technique described by Herrmann and Wang (1985) was used for generating the Rg synthetics for vertically oriented CLVD sources at various depths. The crustal velocity model of Patton and Taylor (1995, Table 1, SMU Velocity Model) was used; the source was assumed to be an impulse. The epicentral distance was taken to be only 20 km since the Rg-to-S scattering is supposed to occur near the explosion source. Figure 9 shows the spectra of Rg for various depths of the CLVD source. It is interesting to note that the increase in the null frequency is slow at first but becomes much larger for shallower depths, remarkably similar to the observed variation in Figure 7. A comparison of the observed null frequencies (Table 1) with the theoretical results in Figure 9 suggests that, on average, depth of the CLVD source for each explosion is about one-third of its shot depth.

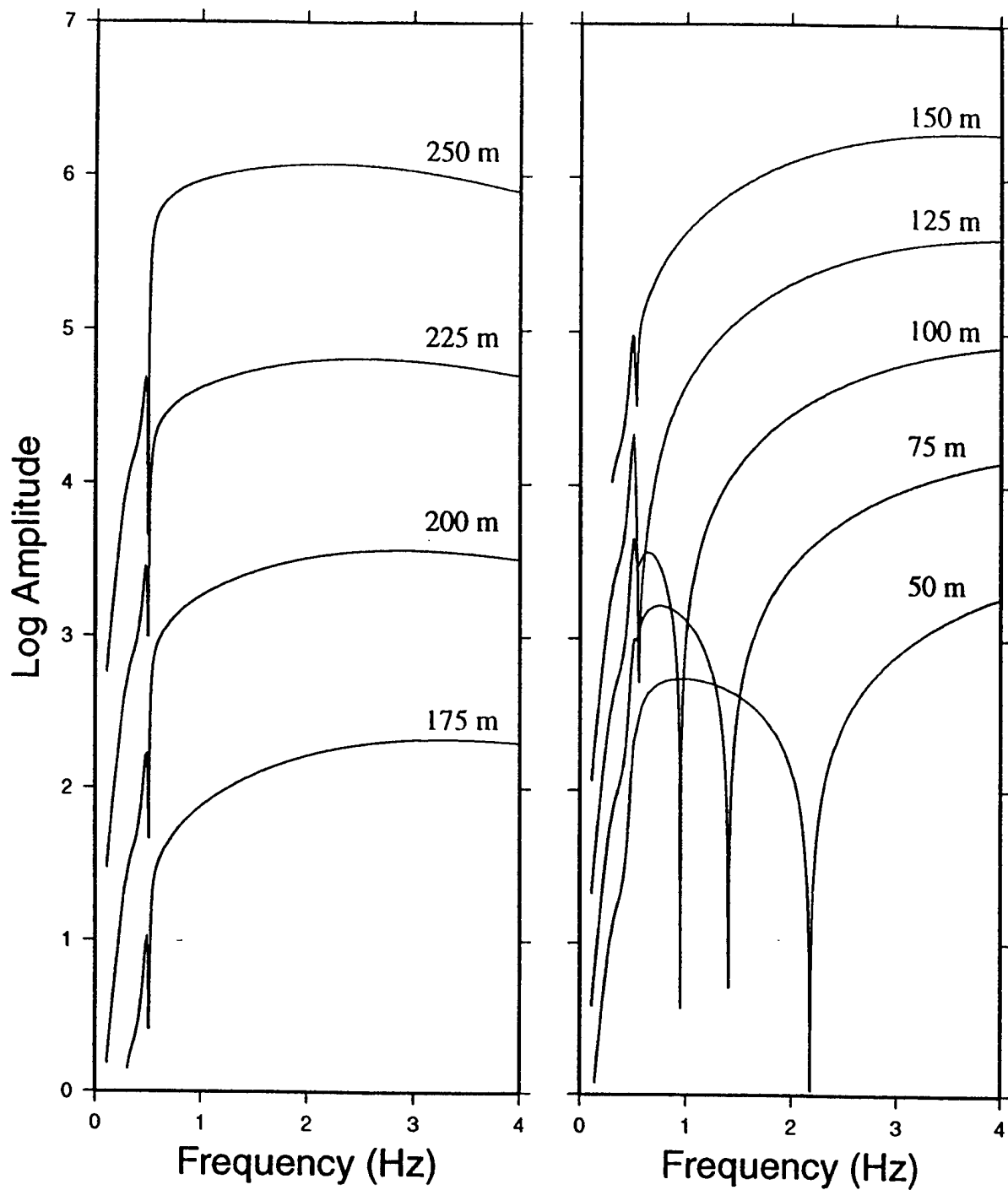


Figure 9. Spectra of Rg synthetics for CLVD source at various depths for crustal velocity model of Yucca Flats used by Patton and Taylor (1995). The increase in the null frequency with source depth is similar to that in Figure 7.

## SPECTRAL NULLS IN Lg FROM KAZAKH EXPLOSIONS

Regional data from the Soviet underground nuclear explosion of the Joint Verification Experiment (JVE, 14 September 1988,  $m_b = 6.03$ ) are available at the three Natural Resources Defense Council (NRDC) stations, KSU, KKL, and BAY. These three stations lie at epicentral distances of about 160 km east, 255 km southwest, and 255 km northwest, respectively. Details of the experiment, sample records, and instrumentation have been provided by Priestley *et al.* (1990). The long and short period seismographs consist of 15 and 1 sec free period seismometers, respectively. Results of NBF analysis of the vertical component long-period data from KKL and BAY and short-period data (after integration using the trapezoidal rule) from KSU (the long-period data at KSU had problems, William Walter, personal communication) are shown in Figures 10, 11, and 12, respectively. These three figures show severe attenuation of Rg for periods less than 1.2-1.3 sec and build-up of the shorter-period S arrivals suggests the scattering of shorter-period Rg into S or Lg. Group velocity of the scattered S is higher than that of Rg, indicating that scattering must take place near the source region. In each figure, a spectral null in Lg (velocity 3.0-3.5 km/sec) is observed at a period of about 0.7 sec.

Regional data from the JVE and several other East Kazakh nuclear explosions are also available at the broadband stations, WMQ (CDSN network) at distances of about 950 km from KTS. Spectral ratios of Lg from the JVE and the much smaller explosion of 12 March 1987, 87071 ( $m_b = 5.31$ ), both recorded at WMQ (vertical component) so that path effects are minimized, are shown in Figure 13(a) for Lg windows of 76.8, 51.2, and 25.6 sec. Each of the three plots shows a spectral null at about 1.4 Hz which corresponds to the null at period of 0.7 sec observed in the NRDC regional data. Furthermore, the plots suggest a maximum at frequency of about 1.8 Hz which may be due to the shallower CLVD source associated with Lg from the smaller explosion, 87071. Spectral ratios of Lg from the explosion of 3 April 1987 (87093), with  $m_b = 6.12$  (somewhat larger and presumably deeper than the JVE) and the smaller explosion 87071, shown in Figure 13(b), also indicate a spectral null at frequency of about 1.1 Hz, likely to be due to the CLVD source associated with the larger explosion 87093. Spectra of Lg (51.2 sec long windows) from 7 explosions from the southwest region of KTS, recorded at WMQ and arranged in order of decreasing  $m_b$ , with Q correction from Xie *et al.* (1996), are shown in Figure 13(c); these also suggest a systematic increase in the Lg null frequency with decreasing  $m_b$  which should be associated with decreasing shot depth, and therefore decreasing depth of the CLVD source. These results suggest that shot depth is important in defining the spectral null in Lg and a determination of the spectral nulls in Lg and comparison with theory should be useful for determination of shot depths and other source and near-source characteristics.

## CHINESE TESTS AT LOP NOR

There is increased interest in nuclear explosions at the Lop Nor test site because, in contrast with the U.S., Russian, and French nuclear test sites, this test site has been active as recently as July 1996. Analysis of Lg from several Lop Nor shots recorded at stations belonging

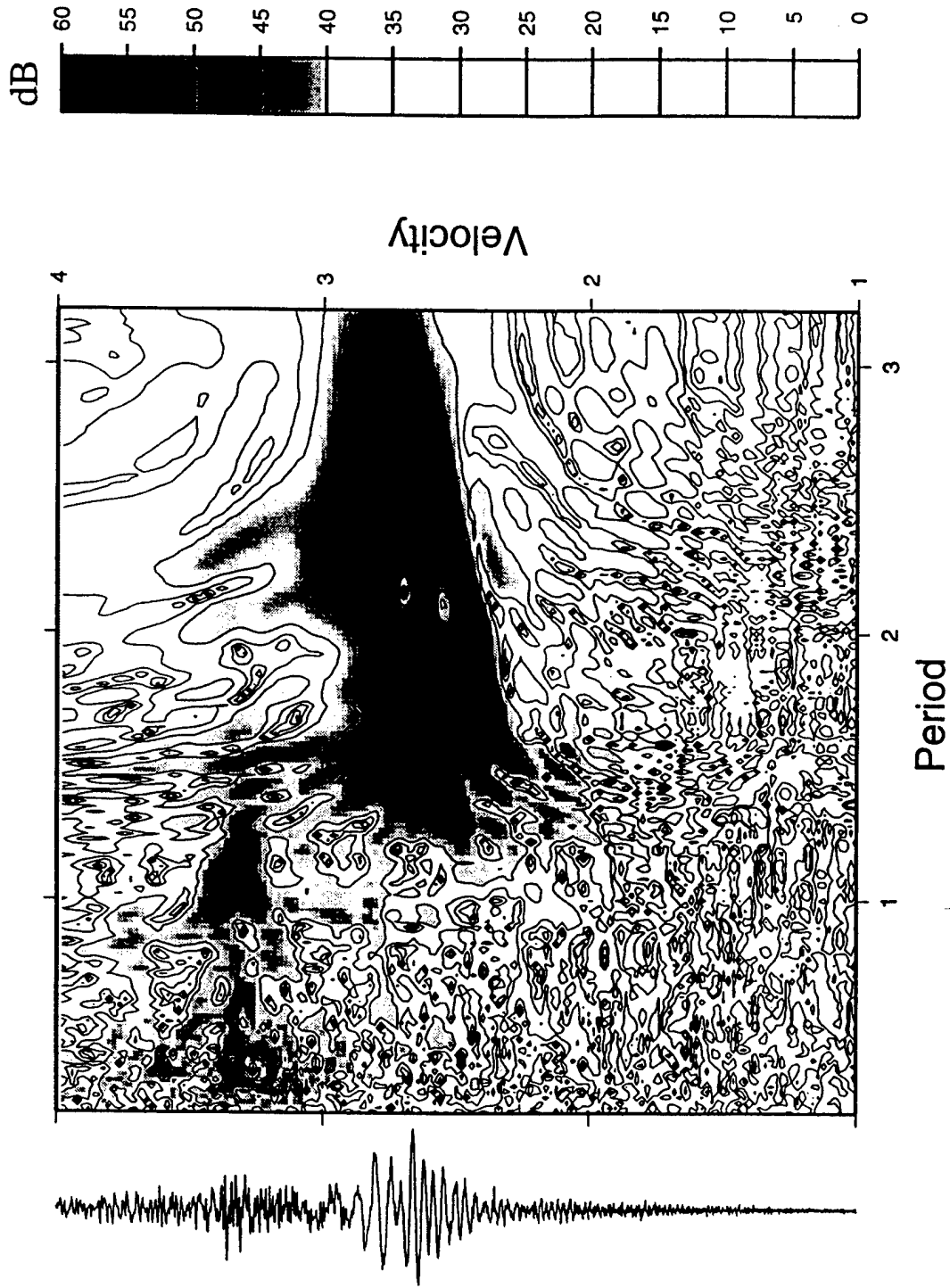


Figure 10. Narrow bandpass filtered record of the Soviet JVE shot of 14 September 1988 at the NRDC station, KKL indicating strong attenuation of Rg for periods less than about 1.2 sec and a spectral null in Lg at a period of about 0.7 sec.

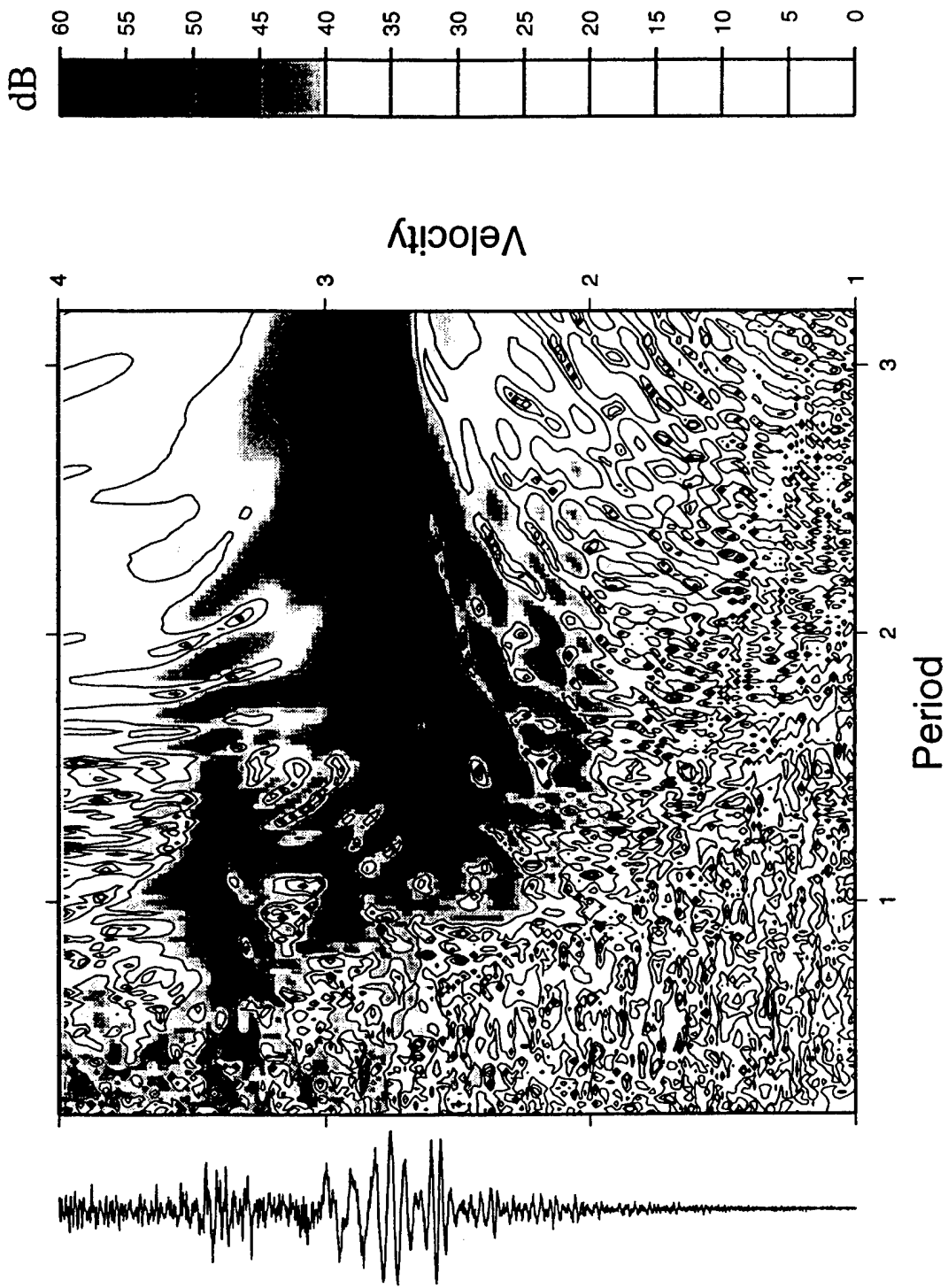


Figure 11. Narrow bandpass filtered record of the Soviet JVE shot of 14 September 1988 at the NRDC station, BAY indicating strong attenuation of Rg for periods less than about 1.1 sec and a spectral null in Lg at a period of about 0.6 sec.

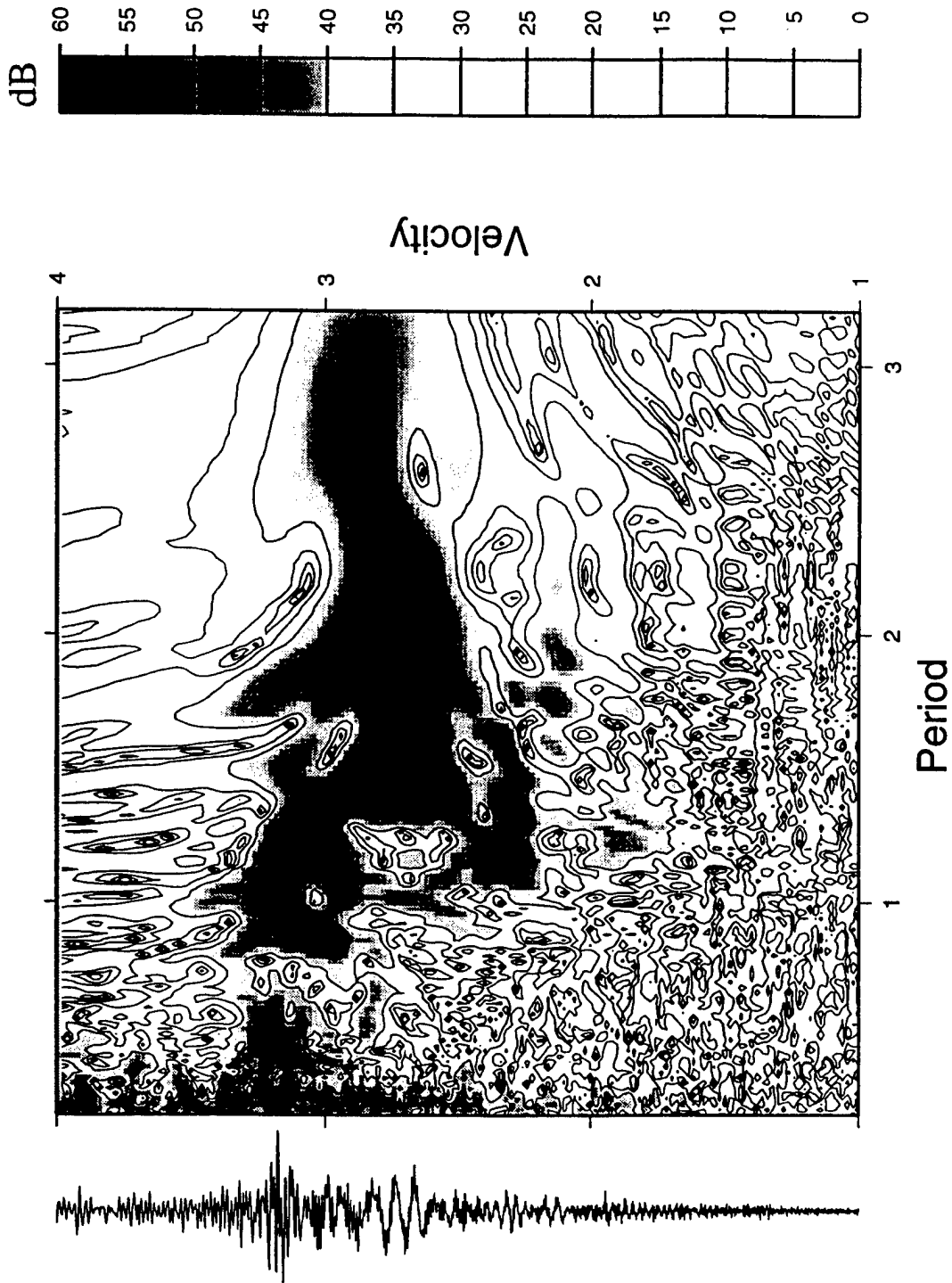


Figure 12. Narrow bandpass filtered record of the Soviet JVE shot of 14 September 1988 at the NRDC station, KRSU indicating strong attenuation of Rg for periods less than about 1.0 sec and a spectral null in Lg at a period of about 0.7 sec.

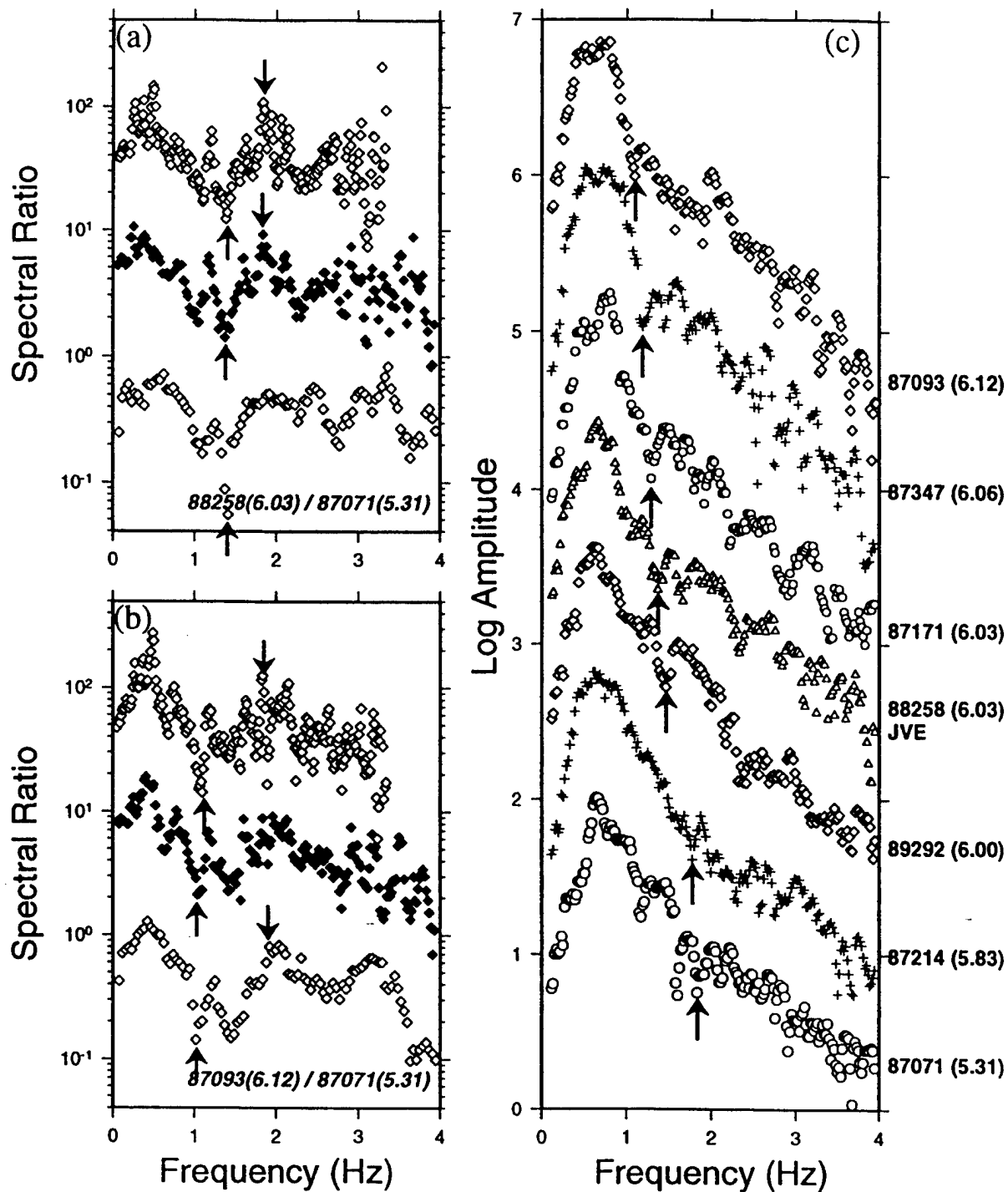


Figure 13. Lg spectral ratios for Kazakh shots recorded at WMQ (a) 88258(JVE)/87071 and (b) 87093/87071 for window lengths of 76.8 sec (top), 51.2 sec (middle), and 25.6 sec (bottom). Each of the three plots in (a) shows a spectral minimum at about 1.4 Hz and a maximum at about 1.9 Hz; plots in (b) indicate a spectral minimum at about 1.1 Hz. (c) Spectra of Lg for 7 Kazakh explosions suggesting a systematic increase in null frequency with decreasing  $m_b$ .

to the Kyrghizstan Network (KNET) showed distinct low-frequency nulls at most stations. Results for 5 shots recorded at the vertical-component broadband KNET station, AAK at epicentral distances of about 1150 km are shown in Figure 14. The individual spectra, with Q correction from Xie *et al.* (1996) (Figure 14a), and the spectral ratios (Figure 14b) indicate the same distinct spectral nulls and a general increase in frequency with decrease in magnitude. Moreover, the null frequencies are similar to those for Kazakh shots (Figure 13) for shots with similar magnitudes.

Matzko (1994) provided a detailed description of the geological structure and rock types at the test site. According to him, the largest shot of 21 May 1992 was emplaced in a shaft over 900 m deep and had a yield of about 1 megaton. Furthermore, the nuclear shots are fired in either vertically drilled shafts or horizontal tunnels but there is hard rock coupling in both areas and the Lop Nor test site is, in several respects, more similar to the KTS than the NTS. This provides a possible explanation for the similarity of the observed Lg null frequencies at KTS (Figure 13) and Lop Nor test site (Figure 14).

### AZGIR PNE AT ILPA ARRAY

Regional data from the salt shot (PNE) of 18 December 1978 ( $m_b = 5.9$ ) at Azgir (north of the Caspian Sea) are available at the ILPA array (Figure 15); see Grant *et al.* (1996). The vertical-component waveforms at two locations, IR1 and IR7 show considerably less energy in Lg than in Sn. A possible reason for the diminished Lg is the presence of mostly oceanic path through the Caspian Sea. Spectra of Lg and Sn windows, each 51.2 sec long and starting at velocities of 3.5 and 4.3 km/sec, respectively, are also shown in Figure 15. Not only the Lg spectra but also the Sn spectra indicate a prominent spectral null at frequency of about 1.1 Hz. It appears therefore that the source of the low frequency energy in the large Sn phase is the same as in Lg and the low-frequency energy in both phases originated from the near-source scattering of Rg into S.

### DISCUSSION AND CONCLUSIONS

Our results fully support Patton and Taylor's (1995) contention that the spectral null in Lg at 0.55 Hz from three normal-depth explosions at the Yucca Flats is primarily due to a CLVD source. However, a few significant differences should be pointed out. The five Yucca Flats explosions used in their study lay close to each other (within about 3 km) and their observational and theoretical results for normal-depth explosions did not show much dependence on shot depth. Our study of low-frequency Lg from a large number of shots with considerable variation in shot depth, combined with theory, clearly indicate that shot depth and subsurface structure are important in defining the spectral null.

Our study of Lg from four distinct test sites indicates that near-source scattering of explosion-generated Rg is an important contributor to the low-frequency Lg from explosions at not only NTS but also in other regions of the world. Broadband data can be effectively used to determine the observed spectral nulls, especially if data from several stations are available so that site effects can be suppressed. Good agreement between observation and theory suggests the

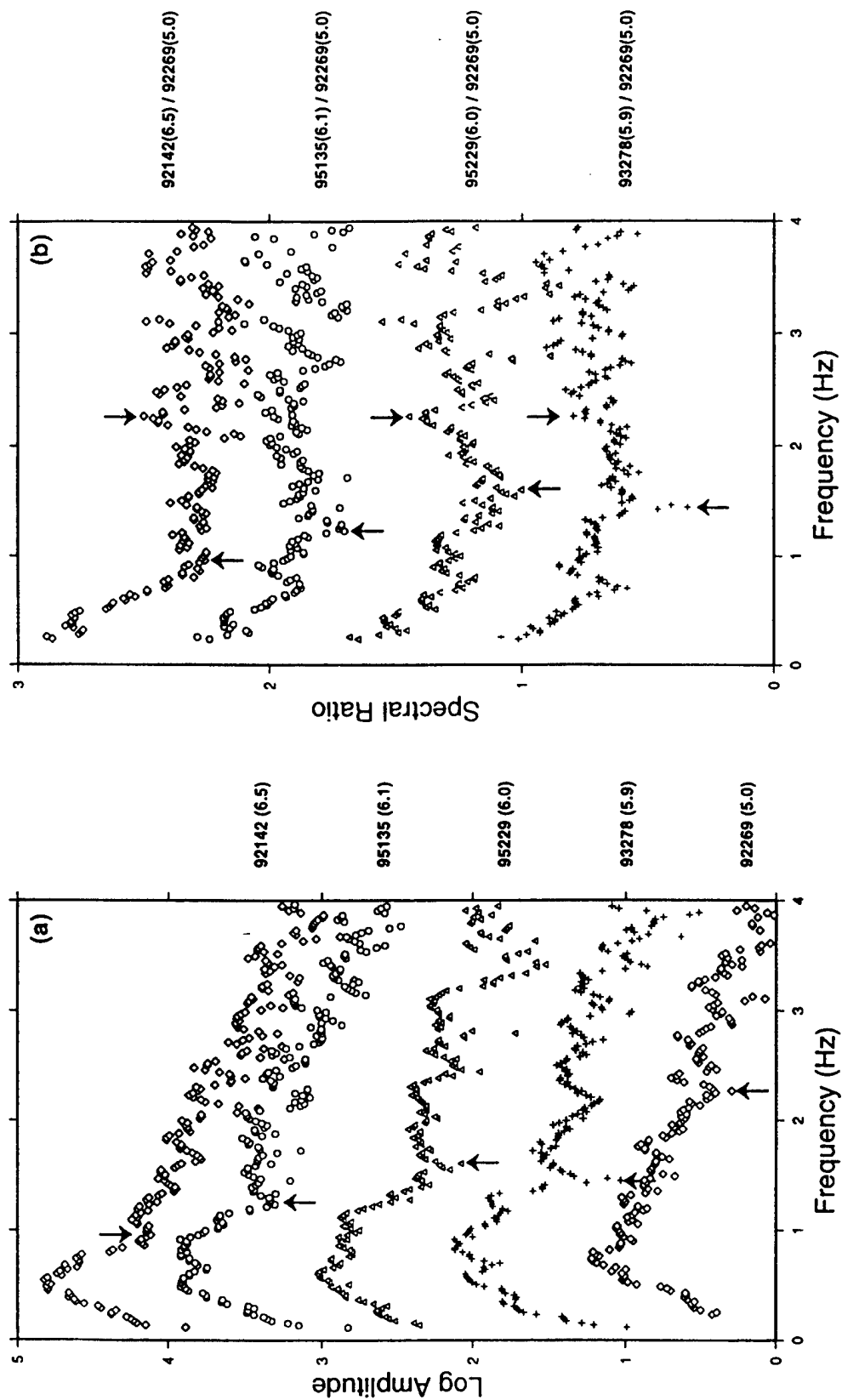


Figure 14. Results from 5 Lop Nor shots recorded at AAK. Both (a) spectra of Lg and (b) spectral ratios indicate the same spectral nulls (indicated by arrows) and a general increase in null frequency with decrease in  $m_b$ .

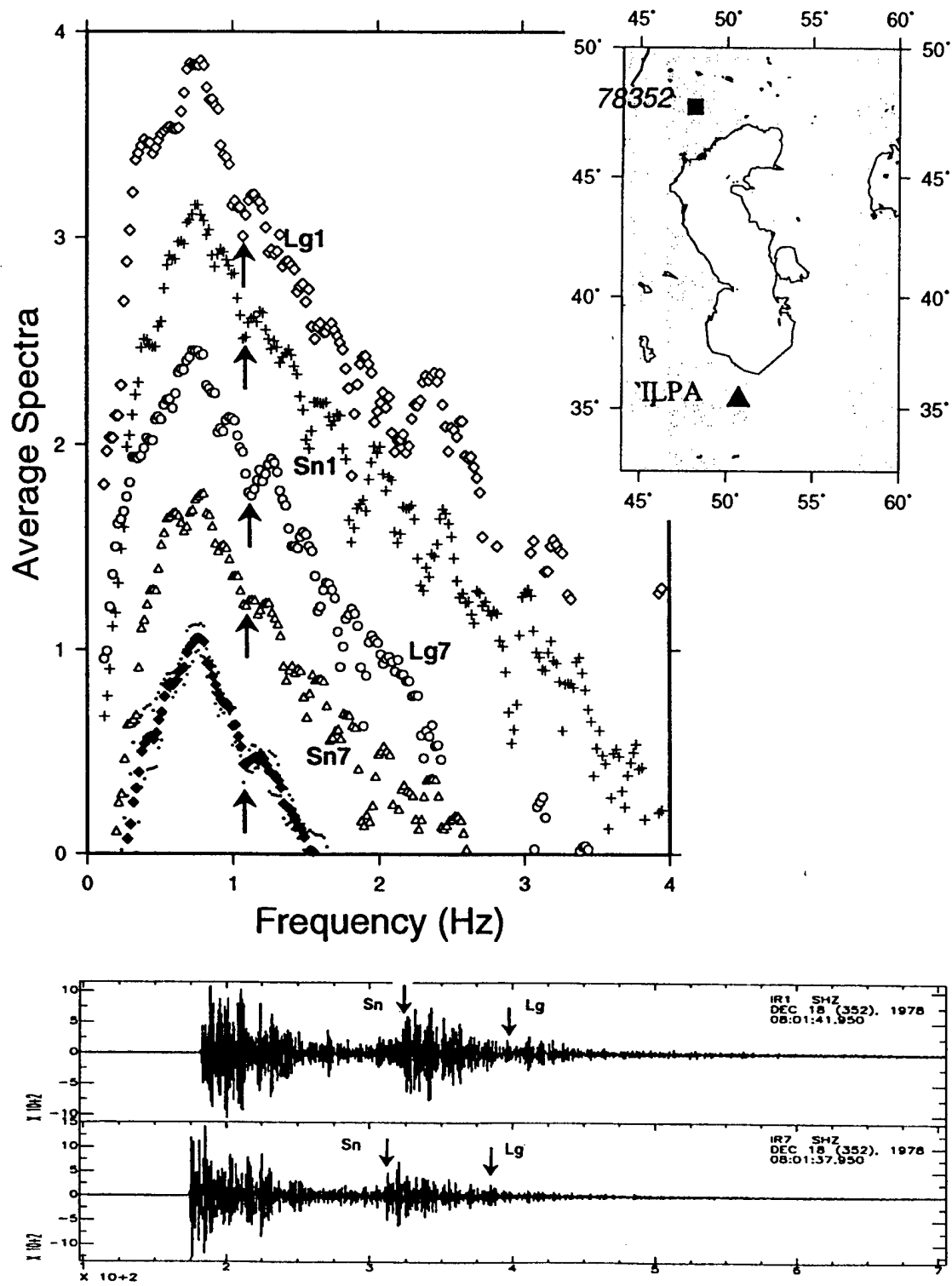


Figure 15. Waveforms and spectra of Lg and Sn from the Azgir PNE (78352) recorded at two ILPA sensors. The four spectra and their average indicate a distinct null at about 1.1 Hz, perhaps due to near-source scattering of explosion-generated Rg into S.

effective CLVD source to be at about one-third the shot depth. Dependence of the Lg spectral nulls on shot depth and local velocity structure provides a method for determining source parameters by comparing theory with observation. Preliminary results from an Azgir PNE also indicate that the near-source scattering of Rg may also make significant contribution to other S phases, such as Sn.

It is recommended that the broadband characteristics of not only Lg but also other phases (especially Sn and Pg) be investigated under various geological settings so that the role of near-source scattering of explosion-generated Rg is clearly understood and exploited for deriving source and near-source information. Representative sets of seismic data covering a wide range of known near-source parameters should be analyzed to understand the generation of both low and high frequency Lg and other regional phases. A comparison of the observations with synthetic seismograms (including finite-difference calculations) should be carried out so that the generation and propagation of regional phases are better understood. These studies will improve the seismic monitoring capability of regional phases by improving their reliability and transportability from one region to another.

## REFERENCES

- Aki, K. and P. G. Richards (1980). Quantitative Seismology, Chapter 7, W. H. Freeman and Company.
- Edwards, C. L. and D. F. Baker (1993). Integrated verification experiment data collected as part of the Los Alamos National Laboratory's source region program, Appendix E: Local and near-regional data for IVEs, LAUR-93-854, Los Alamos National Laboratory, Los Alamos, New Mexico.
- Grant, L., F. Ryall, I. Henson, and W. Rivers (1996). Ground truth database for seismic discrimination research, *in* Proceedings of the 18th Annual Seismic Research Symposium on Monitoring a Comprehensive Test Ban Treaty, 4-6 September 1996, *PL-TR-96-2153*, 997-1006, ADA313692.
- Gupta, I. N., W. W. Chan, and R. A. Wagner (1992). A comparison of regional phases from underground nuclear explosions at East Kazakh and Nevada test sites, *Bull. Seism. Soc. Am.* 82, 352-382.
- Gupta, I. N., C. S. Lynnes, and R. A. Wagner (1991). Studies of near-source and near-receiver scattering and low-frequency Lg from East Kazakh and NTS explosions, *PL-TR-91-2287*, Phillips Laboratory, Hanscom Air Force Base, Massachusetts, ADA248046.
- Gupta, I. N. and T. R. Zhang (1996). Mechanism of generation of low-frequency Lg from NTS explosions - observations and interpretation, *Seismol. Res. Lett.* 67 (2), 40.
- Herrmann, R. B. and C. Y. Wang (1985). A comparison of synthetic seismograms, *Bull. Seism. Soc. Am.* 75, 41-56.
- Israelsson, H. (1992). A spectral decomposition of Lg waves from explosions and scaling of RMS magnitudes, *in* RMS Lg as a yield estimator in Eurasia, *PL-TR-92-2117(I)*, 143-166, Phillips Laboratory, Hanscom Air Force Base, Massachusetts, ADA256692.
- Kafka, A. L. (1990). Rg as a depth discriminant for earthquakes and explosions: a case study in New England, *Bull. Seism. Soc. Am.* 80, 373-394.
- Matzko, J. R. (1994). Geology of the Chinese nuclear test site near Lop Nor, Xinjiang Uygur Autonomous Region, China, *Engineering Geology* 36, 173-181.
- Patton, H. J. (1988). Application of Nuttli's method to estimate yield of Nevada Test Site explosions recorded on Lawrence Livermore National Laboratory's digital seismic system, *Bull. Seism. Soc. Am.* 78, 1759-1772.

Patton, H. J. and S. R. Taylor (1995). Analysis of Lg spectral ratios from NTS explosions: implications for the source mechanisms of spall and the generation of Lg waves, *Bull. Seism. Soc. Am.* 85, 220-236.

Priestley, K. F., W. R. Walter, V. Martynov, and M. V. Rozhkov (1990). Regional seismic recordings of the Soviet nuclear explosion of the Joint Verification Experiment, *Geophys. Res. Lett.* 17, 179-182.

Seneff, S. (1978). A fast new method for frequency-filter analysis of surface waves: application in the west Pacific, *Bull. Seism. Soc. Am.* 68, 1031-1048.

Taylor, S. R. (1993). Integrated verification experiment data collected as part of the Los Alamos National Laboratory's source region program, Appendix F: Regional data from Lawrence Livermore National Laboratory and Sandia National Laboratory seismic networks, LAUR-93-2150, Los Alamos National Laboratory, Los Alamos, New Mexico.

Xie, J., L. Cong, and B. J. Mitchell (1996). Spectral characteristics of the excitation and propagation of Lg from underground nuclear explosions in central Asia, *J. Geophys. Res.* 101, 5813-5822.

#### ACKNOWLEDGMENTS

In addition to the Principal Investigator, Tian-Run Zhang, David Salzberg, Claudia Carabajal, and Winston Chan contributed to this study. We sincerely thank William Walter of the Lawrence Livermore Laboratory and the IRIS staff for providing some of the data used in this study. Thanks are also due to Winston Chan and Wilmer Rivers for general guidance and a critical review of the manuscript.

THOMAS AHRENS  
SEISMOLOGICAL LABORATORY 252-21  
CALIFORNIA INSTITUTE OF TECHNOLOGY  
PASADENA, CA 91125

SHELTON ALEXANDER  
PENNSYLVANIA STATE UNIVERSITY  
DEPARTMENT OF GEOSCIENCES  
537 DEIKE BUILDING  
UNIVERSITY PARK, PA 16801

RICHARD BARDZELL  
ACIS  
DCI/ACIS  
WASHINGTON, DC 20505

DOUGLAS BAUMGARDT  
ENSCO INC.  
5400 PORT ROYAL ROAD  
SPRINGFIELD, VA 22151

WILLIAM BENSON  
NAS/COS  
ROOM HA372  
2001 WISCONSIN AVE. NW  
WASHINGTON, DC 20007

ROBERT BLANDFORD  
AFTAC  
1300 N. 17TH STREET  
SUITE 1450  
ARLINGTON, VA 22209-2308

RHETT BUTLER  
IRIS  
1616 N. FORT MEYER DRIVE  
SUITE 1050  
ARLINGTON, VA 22209

CATHERINE DE GROOT-HEDLIN  
SCRIPPS INSTITUTION OF OCEANOGRAPHY  
UNIVERSITY OF CALIFORNIA, SAN DIEGO  
INSTITUTE OF GEOPHYSICS AND PLANETARY PHYSICS  
LA JOLLA, CA 92093

SEAN DORAN  
ACIS  
DCI/ACIS  
WASHINGTON, DC 20505

RICHARD J. FANTEL  
BUREAU OF MINES  
DEPT OF INTERIOR, BLDG 20  
DENVER FEDERAL CENTER  
DENVER, CO 80225

RALPH ALEWINE  
NTPO  
1901 N. MOORE STREET, SUITE 609  
ARLINGTON, VA 22209

MUAWIA BARAZANGI  
INSTITUTE FOR THE STUDY OF THE CONTINENTS  
3126 SNEE HALL  
CORNELL UNIVERSITY  
ITHACA, NY 14853

T.G. BARKER  
MAXWELL TECHNOLOGIES  
P.O. BOX 23558  
SAN DIEGO, CA 92123

THERON J. BENNETT  
MAXWELL TECHNOLOGIES  
11800 SUNRISE VALLEY DRIVE SUITE 1212  
RESTON, VA 22091

JONATHAN BERGER  
UNIVERSITY OF CA, SAN DIEGO  
SCRIPPS INSTITUTION OF OCEANOGRAPHY IGPP, 0225  
9500 GILMAN DRIVE  
LA JOLLA, CA 92093-0225

STEVEN BRATT  
NTPO  
1901 N. MOORE STREET, SUITE 609  
ARLINGTON, VA 22209

LESLIE A. CASEY  
DOE  
1000 INDEPENDENCE AVE. SW  
NN-40  
WASHINGTON, DC 20585-0420

STANLEY DICKINSON  
AFOSR  
110 DUNCAN AVENUE, SUITE B115  
BOLLING AFB  
WASHINGTON, D.C. 20332-001

DIANE I. DOSER  
DEPARTMENT OF GEOLOGICAL SCIENCES  
THE UNIVERSITY OF TEXAS AT EL PASO  
EL PASO, TX 79968

JOHN FILSON  
ACIS/TMG/NTT  
ROOM 6T11 NHB  
WASHINGTON, DC 20505

MARK D. FISK  
MISSION RESEARCH CORPORATION  
735 STATE STREET  
P.O. DRAWER 719  
SANTA BARBARA, CA 93102-0719

LORI GRANT  
MULTIMAX, INC.  
311C FOREST AVE. SUITE 3  
PACIFIC GROVE, CA 93950

I. N. GUPTA  
MULTIMAX, INC.  
1441 MCCORMICK DRIVE  
LARGO, MD 20774

JAMES HAYES  
NSF  
4201 WILSON BLVD., ROOM 785  
ARLINGTON, VA 22230

MICHAEL HEDLIN  
UNIVERSITY OF CALIFORNIA, SAN DIEGO  
SCRIPPS INSTITUTION OF OCEANOGRAPHY IGPP, 0225  
9500 GILMAN DRIVE  
LA JOLLA, CA 92093-0225

EUGENE HERRIN  
SOUTHERN METHODIST UNIVERSITY  
DEPARTMENT OF GEOLOGICAL SCIENCES  
DALLAS, TX 75275-0395

VINDELL HSU  
HQ/AFTAC/TTR  
1030 S. HIGHWAY A1A  
PATRICK AFB, FL 32925-3002

RONG-SONG JIH  
PHILLIPS LABORATORY  
EARTH SCIENCES DIVISION  
29 RANDOLPH ROAD  
HANSCOM AFB, MA 01731-3010

LAWRENCE LIVERMORE NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
PO BOX 808, MS L-200  
LIVERMORE, CA 94551

LAWRENCE LIVERMORE NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
PO BOX 808, MS L-221  
LIVERMORE, CA 94551

ROBERT GEIL  
DOE  
PALAIS DES NATIONS, RM D615  
GENEVA 10, SWITZERLAND

HENRY GRAY  
SMU STATISTICS DEPARTMENT  
P.O. BOX 750302  
DALLAS, TX 75275-0302

DAVID HARKRIDER  
PHILLIPS LABORATORY  
EARTH SCIENCES DIVISION  
29 RANDOLPH ROAD  
HANSCOM AFB, MA 01731-3010

THOMAS HEARN  
NEW MEXICO STATE UNIVERSITY  
DEPARTMENT OF PHYSICS  
LAS CRUCES, NM 88003

DONALD HELMBERGER  
CALIFORNIA INSTITUTE OF TECHNOLOGY  
DIVISION OF GEOLOGICAL & PLANETARY SCIENCES  
SEISMOLOGICAL LABORATORY  
PASADENA, CA 91125

ROBERT HERRMANN  
ST. LOUIS UNIVERSITY  
DEPARTMENT OF EARTH & ATMOSPHERIC SCIENCES  
3507 LACLEDE AVENUE  
ST. LOUIS, MO 63103

ANTHONY IANNACCHIONE  
BUREAU OF MINES  
COCHRANE MILL ROAD  
PO BOX 18070  
PITTSBURGH, PA 15236-9986

THOMAS JORDAN  
MASSACHUSETTS INSTITUTE OF TECHNOLOGY  
EARTH, ATMOSPHERIC & PLANETARY SCIENCES  
77 MASSACHUSETTS AVENUE, 54-918  
CAMBRIDGE, MA 02139

LAWRENCE LIVERMORE NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
PO BOX 808, MS L-207  
LIVERMORE, CA 94551

LAWRENCE LIVERMORE NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
LLNL  
PO BOX 808, MS L-175  
LIVERMORE, CA 94551

LAWRENCE LIVERMORE NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
PO BOX 808, MS L-208  
LIVERMORE, CA 94551

LAWRENCE LIVERMORE NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
PO BOX 808, MS L-202  
LIVERMORE, CA 94551

LAWRENCE LIVERMORE NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
PO BOX 808, MS L-195  
LIVERMORE, CA 94551

LAWRENCE LIVERMORE NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
PO BOX 808, MS L-205  
LIVERMORE, CA 94551

THORNE LAY  
UNIVERSITY OF CALIFORNIA, SANTA CRUZ  
EARTH SCIENCES DEPARTMENT  
EARTH & MARINE SCIENCE BUILDING  
SANTA CRUZ, CA 95064

ANATOLI L. LEVSHIN  
DEPARTMENT OF PHYSICS  
UNIVERSITY OF COLORADO  
CAMPUS BOX 390  
BOULDER, CO 80309-0309

DONALD A. LINGER  
DNA  
6801 TELEGRAPH ROAD  
ALEXANDRIA, VA 22310

LOS ALAMOS NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
PO BOX 1663, MS F659  
LOS ALAMOS, NM 87545

LOS ALAMOS NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
PO BOX 1663, MS F665  
LOS ALAMOS, NM 87545

LOS ALAMOS NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
PO BOX 1663, MS D460  
LOS ALAMOS, NM 87545

LOS ALAMOS NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
PO BOX 1663, MS C335  
LOS ALAMOS, NM 87545

GARY MCCARTOR  
SOUTHERN METHODIST UNIVERSITY  
DEPARTMENT OF PHYSICS  
DALLAS, TX 75275-0395

KEITH MCLAUGHLIN  
MAXWELL TECHNOLOGIES  
P.O. BOX 23558  
SAN DIEGO, CA 92123

BRIAN MITCHELL  
DEPARTMENT OF EARTH & ATMOSPHERIC SCIENCES  
ST. LOUIS UNIVERSITY  
3507 LACLEDE AVENUE  
ST. LOUIS, MO 63103

RICHARD MORROW  
USACDA/VI  
320 21ST STREET, N.W.  
WASHINGTON, DC 20451

JOHN MURPHY  
MAXWELL TECHNOLOGIES  
11800 SUNRISE VALLEY DRIVE SUITE 1212  
RESTON, VA 22091

JAMES NI  
NEW MEXICO STATE UNIVERSITY  
DEPARTMENT OF PHYSICS  
LAS CRUCES, NM 88003

JOHN ORCUTT  
INSTITUTE OF GEOPHYSICS AND PLANETARY PHYSICS  
UNIVERSITY OF CALIFORNIA, SAN DIEGO  
LA JOLLA, CA 92093

PACIFIC NORTHWEST NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
PO BOX 999, MS K6-48  
RICHLAND, WA 99352

PACIFIC NORTHWEST NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
PO BOX 999, MS K7-34  
RICHLAND, WA 99352

PACIFIC NORTHWEST NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
PO BOX 999, MS K6-40  
RICHLAND, WA 99352

PACIFIC NORTHWEST NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
PO BOX 999, MS K7-22  
RICHLAND, WA 99352

PACIFIC NORTHWEST NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
PO BOX 999, MS K5-72  
RICHLAND, WA 99352

PACIFIC NORTHWEST NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
PO BOX 999, MS K6-84  
RICHLAND, WA 99352

PACIFIC NORTHWEST NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
PO BOX 999, MS K5-12  
RICHLAND, WA 99352

FRANK PILOTTE  
HQ/AFTAC/TT  
1030 S. HIGHWAY A1A  
PATRICK AFB, FL 32925-3002

KEITH PRIESTLEY  
DEPARTMENT OF EARTH SCIENCES  
UNIVERSITY OF CAMBRIDGE  
MADINGLEY RISE, MADINGLEY ROAD  
CAMBRIDGE, CB3 0EZ UK

JAY PULLI  
RADIX SYSTEMS, INC.  
6 TAFT COURT  
ROCKVILLE, MD 20850

PAUL RICHARDS  
COLUMBIA UNIVERSITY  
LAMONT-DOHERTY EARTH OBSERVATORY  
PALISADES, NY 10964

DAVID RUSSELL  
HQ AFTAC/TTR  
1030 SOUTH HIGHWAY A1A  
PATRICK AFB, FL 32925-3002

CHANDAN SAIKIA  
WOODWARD-CLYDE FEDERAL SERVICES  
566 EL DORADO ST., SUITE 100  
PASADENA, CA 91101-2560

SANDIA NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
DEPT. 5704  
MS 0979, PO BOX 5800  
ALBUQUERQUE, NM 87185-0979

SANDIA NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
DEPT. 5791  
MS 0567, PO BOX 5800  
ALBUQUERQUE, NM 87185-0567

SANDIA NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
DEPT. 9311  
MS 1159, PO BOX 5800  
ALBUQUERQUE, NM 87185-1159

SANDIA NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
DEPT. 5704  
MS 0655, PO BOX 5800  
ALBUQUERQUE, NM 87185-0655

SANDIA NATIONAL LABORATORY  
ATTN: TECHNICAL STAFF (PLS ROUTE)  
DEPT. 5736  
MS 0655, PO BOX 5800  
ALBUQUERQUE, NM 87185-0655

THOMAS SERENO JR.  
SCIENCE APPLICATIONS INTERNATIONAL  
CORPORATION  
10260 CAMPUS POINT DRIVE  
SAN DIEGO, CA 92121

AVI SHAPIRA  
SEISMOLOGY DIVISION  
THE INSTITUTE FOR PETROLEUM RESEARCH AND  
GEOPHYSICS  
P.O.B. 2286, NOLON 58122 ISRAEL

ROBERT SHUMWAY  
410 MRAK HALL  
DIVISION OF STATISTICS  
UNIVERSITY OF CALIFORNIA  
DAVIS, CA 95616-8671

MATTHEW SIBOL  
ENSCO, INC.  
445 PINEDA COURT  
MELBOURNE, FL 32940

DAVID SIMPSON  
IRIS  
1616 N. FORT MEYER DRIVE  
SUITE 1050  
ARLINGTON, VA 22209

BRIAN SULLIVAN  
BOSTON COLLEGE  
INSITUTE FOR SPACE RESEARCH  
140 COMMONWEALTH AVENUE  
CHESTNUT HILL, MA 02167

NAFI TOKSOZ  
EARTH RESOURCES LABORATORY, M.I.T.  
42 CARLTON STREET, E34-440  
CAMBRIDGE, MA 02142

GREG VAN DER VINK  
IRIS  
1616 N. FORT MEYER DRIVE  
SUITE 1050  
ARLINGTON, VA 22209

TERRY WALLACE  
UNIVERSITY OF ARIZONA  
DEPARTMENT OF GEOSCIENCES  
BUILDING #77  
TUCSON, AZ 85721

JAMES WHITCOMB  
NSF  
NSF/ISC OPERATIONS/EAR-785  
4201 WILSON BLVD., ROOM785  
ARLINGTON, VA 22230

JIAKANG XIE  
COLUMBIA UNIVERSITY  
LAMONT DOHERTY EARTH OBSERVATORY  
ROUTE 9W  
PALISADES, NY 10964

OFFICE OF THE SECRETARY OF DEFENSE  
DDR&E  
WASHINGTON, DC 20330

TACTEC  
BATTELLE MEMORIAL INSTITUTE  
505 KING AVENUE  
COLUMBUS, OH 43201 (FINAL REPORT)

PHILLIPS LABORATORY  
ATTN: GPE  
29 RANDOLPH ROAD  
HANSCOM AFB, MA 01731-3010

JEFFRY STEVENS  
MAXWELL TECHNOLOGIES  
P.O. BOX 23558  
SAN DIEGO, CA 92123

DAVID THOMAS  
ISEE  
29100 AURORA ROAD  
CLEVELAND, OH 44139

LAWRENCE TURNBULL  
ACIS  
DCI/ACIS  
WASHINGTON, DC 20505

FRANK VERNON  
UNIVERSITY OF CALIFORNIA, SAN DIEGO  
SCRIPPS INSTITUTION OF OCEANOGRAPHY IGPP, 0225  
9500 GILMAN DRIVE  
LA JOLLA, CA 92093-0225

DANIEL WEILL  
NSF  
EAR-785  
4201 WILSON BLVD., ROOM 785  
ARLINGTON, VA 22230

RU SHAN WU  
UNIVERSITY OF CALIFORNIA SANTA CRUZ  
EARTH SCIENCES DEPT.  
1156 HIGH STREET  
SANTA CRUZ, CA 95064

JAMES E. ZOLLWEG  
BOISE STATE UNIVERSITY  
GEOSCIENCES DEPT.  
1910 UNIVERSITY DRIVE  
BOISE, ID 83725

DEFENSE TECHNICAL INFORMATION CENTER  
8725 JOHN J. KINGMAN ROAD  
FT BELVOIR, VA 22060-6218 (2 COPIES)

PHILLIPS LABORATORY  
ATTN: XPG  
29 RANDOLPH ROAD  
HANSCOM AFB, MA 01731-3010

PHILLIPS LABORATORY  
ATTN: TSML  
5 WRIGHT STREET  
HANSCOM AFB, MA 01731-3004

PHILLIPS LABORATORY  
ATTN: PL/SUL  
3550 ABERDEEN AVE SE  
KIRTLAND, NM 87117-5776 (2 COPIES)