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Spectral Discrimination between Explosions and Earthquakes in Central Eurasia

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13. ABSTRACT *(Maximum 200 words)*

An analysis is performed of the seismic discrimination capabilities of regional phases recorded at the station WMQ in the Chinese Digital Seismic Network (CDSN). This station is located at regional distances from both the Soviet test site in E. Kazakhstan and the seismically active Tien Shan area. The study is based on 3 spectral ratio discriminants: Pg/Lg spectral ratios, Pg and Lg frequency band ratios, and vertical/horizontal spectral ratios. Both short-period and broad-band data are used. The Pg/Lg ratio is an effective discriminant between 3 and 12 Hz, and the vertical/horizontal ratios perform similarly to it, although in the case of Lg more study is needed to explain the value of this ratio. The Pg and Lg frequency band ratios were ineffective discriminants. The study attempts to identify the effects of propagation path and event depth on the discriminants. It appears that the spectral ratio discriminant remains effective for 2 earthquakes observed along paths close to the path from the test site to WMQ. In the scale of kilometers, event depth does control the Pg and Lg spectral ratios, but it is unlikely that this effect is observable in the scale of meters. Keywords: Seismic data discrimination;

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EXECUTIVE SUMMARY

Regional spectral discriminants have been the subject of several intensive studies in recent years due to the establishment of in-country seismic monitoring system in the Soviet Union. Moreover, with the advance made in high dynamic range, broad-band instruments, these spectral discriminants may then be quantified. This study will analyze the discriminatory capabilities of these spectral discriminants using seismic data collected from a system of state-of-the-art seismic instruments installed in western China. The proximity of this station (WMQ) to the Soviet test sites in E. Kazakh and the active earthquake zones in the Tien Shan region makes it an excellent source of data for such a regional discrimination study.

Three spectral ratio discriminants are studied, namely Pg and Lg spectral phase ratioing, Pg and Lg frequency band ratioing, and three-component spectral ratioing. These discriminants are evaluated using a similar data set analyzed under a standard windowing and processing criterion. The Pg and Lg spectral ratio performs very well in discriminating between earthquakes and explosions between the frequency range of 3 to 12 Hz. The Pg and Lg frequency band ratioing does not show to be a promising discriminant, but it provides insight to the understanding of spectra characteristics for earthquakes and explosions. The three component analysis performs very similarly to the Pg and Lg spectral ratio discriminant, but the unpredicted low level of the ratios between horizontal and vertical components of Lg for explosions warrants further analysis.

Various parameters that might have influenced the characteristics of the spectral ratios have been investigated, including depth effect, frequency effect, and path effect. By studying spectral ratios for earthquakes traversing along paths similar to those of the explosions, it was concluded that the spectral ratio discriminant remains effective. Although it is discovered that the depth of the seismic events has a controlling effect in the level of the Lg and Pg spectral ratios in a kilometer scale, it is unlikely that such effect is observable in the meter scale. This study has shown that in Central Eurasia, using events in and around the station WMQ, the spectral discriminant appears to be an effective one. To further establish this discriminant, studies need to be performed in regions with an abundance of ground-truth geological information, thus allowing an in-depth understanding of the mechanism underlying such discriminant.

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1.0 INTRODUCTION

With the increasing network capability of the seismic monitoring system in the Soviet Union, regional discrimination has become a very important issue. High frequency studies of regional phases have demonstrated the significance of high frequency regional discriminants and revealed some very important observations. The various studies of Bakun and Johnson (1908), Murphy and Bennett (1982), Bennett and Murphy (1989), and Taylor (1988) have found certain regional spectral ratio discriminants to be effective under particular geological criteria and presented opposing analysis for such a discriminant in other criteria. The underlying mechanism for such a discriminant to perform satisfactorily remains unknown and may be attributed to our lack of understanding towards the generation of the *Lg* phase. Leading hypotheses of *Lg* generation include *P-S* conversion at the free surface, scattering of body wave energy, and generation of the non-geometrical *S** phase (Gutowski *et al.*, 1984).

Short period regional discrimination relies heavily on regional phases *Pn*, *Pg*, and *Lg* which are well excited at regional distances of up to approximately 25°. For small to moderate sized seismic events, these phases are best observed on short-period and broad-band seismographs. It is through the advance made in high dynamic range, broad-band instruments that these discriminants can be tested. In particular, this study will focus on investigating the ability to discriminate between earthquakes and nuclear explosions through spectral ratio analysis of these regional phases in central Eurasia. The excitation and propagation parameters of the regional crustal phases will be quantified. Geological assessments of the regions of interest will aid in the interpretation of regional variations of crustal propagation characteristics.

To further exploit the capability of the regional seismic phases *Pn, Pg, Sn*, and *Lg* in discrimination problems, it is important to understand fully the excitation and propagation of these phases across a wide variety of tectonic and geological regions for quarry blasts, earthquakes and nuclear explosions. Discriminants and yield estimation corrections may not be applied uniformly without regional constraints, owing to the effect of varying site geologies and propagation paths. In addition to reflecting the source characteristics, the discriminants may also be affected by regional variations in attenuation properties, and in crustal structure between each seismic source and the various receivers. The path attenuation effects are crucial in seismic yield estimation since the amplitudes are heavily dependent on the efficiency of the propagation of the high-frequency regional phases. Propagation of regional phases generated by seismic events has been widely studied to measure their attenuation properties for corrections to yield estimates. In particular, *Lg* is most commonly used to investigate various regions of the world due to its efficient propagation at regional distances (*e.g.*, Nuttli, 1973, 1980; Gupta and Burnetti, 1980; Hasegawa, 1985; Campillo *et al.*, 1985). In most of these studies, the attenuation effects have been estimated by assuming some preferred forms of the geometrical spreading-dispersion effect and fitting Q(f). In recent studies by Nuttli (1986a,b), very different attenuation corrections are required for estimating the yields of NTS and East Kazakh events from regional data.

In general, there is little agreement among the various investigators as to the value of relative amplitudes and frequency contents of crustal arrivals for discriminating between earthquakes, quarry blasts, and nuclear explosions. The dominant phase velocities of *Lg* have been found to depend on the source depth (Barley, 1979), and *Lg* excitation is observed to decrease with increasing source depth compared to *P* (Noponen and Burnetti, 1980). Murphy and Bennett (1982) claim that at UBO, explosion spectra have a lower frequency content than earthquake spectra. Recently, the implications of high-frequency regional propagation characteristics of various crustal phases with regards to detectability and discrimination capability for decoupled nuclear explosions by a hypothetical internal network in the USSR were discussed by Evernden *et al.* (1986). Their study was based on certain assumptions of the frequency dependence of Q and assumptions of the source spectral slope, and it may therefore be limited in bandwidth and geographical coverage.

Digital seismic data from the China Digital Seismic Network (CDSN) is utilized to study the regional propagation of high-frequency seismic phases in Eurasia at relatively close-range distances. This study utilizes high-frequency and broad-band seismic data from the station WMQ in Wulumuqi, Xianjiang, China belonging to the CDSN. These instruments yield high quality regional phase data of up to 20 Hz, allowing us to perform studies in using both spectral ratio and phase ratio methods for the different bands of recordings. The deployment of the CDSN network has made it possible to study the propagation of regional phases in Eurasia at distances of less than 15° (Fig. 1). The proximity of these stations to the test sites in the Soviet Union and China has provided data with excellently recorded *Pn, Sn, Lg*, and *Pg* at regional distances. These data constitute an excellent database for research towards understanding the underlying properties governing the excitation and propagation of seismic waves in the stable and tectonic regions of Eurasia.

Events used for P/Lg
in Central Eurasia

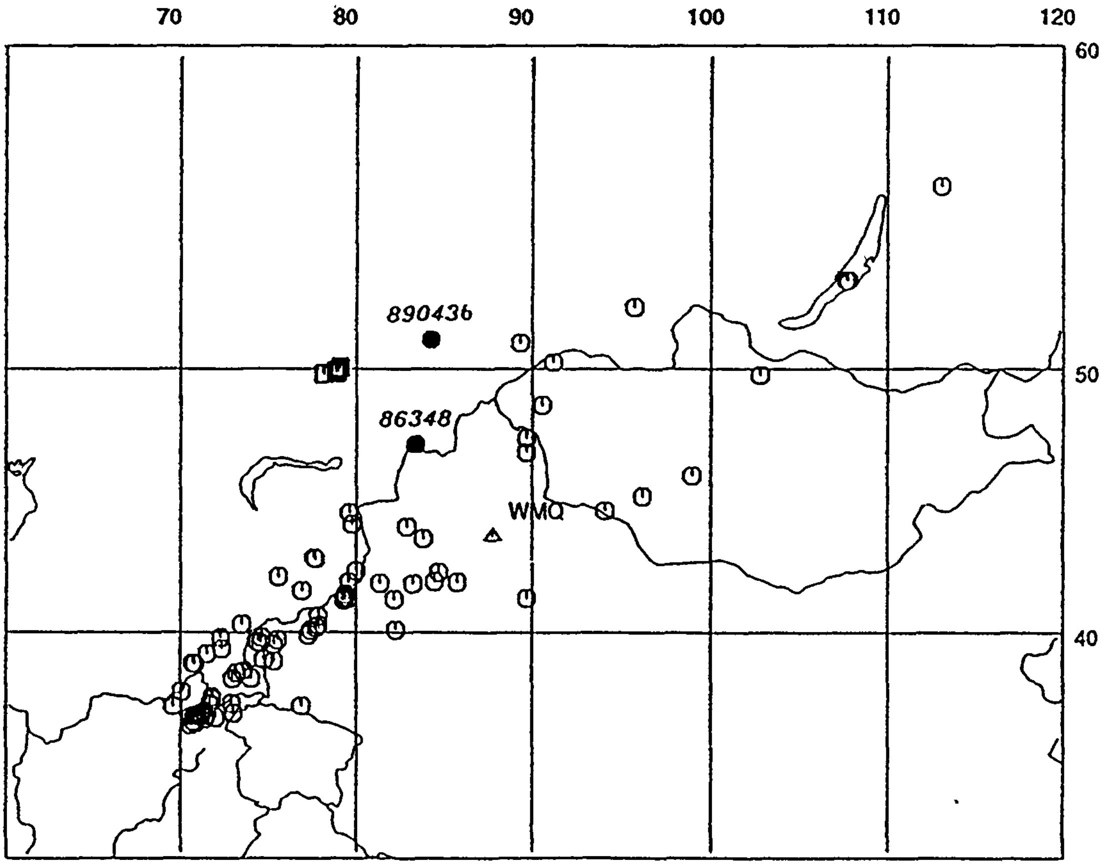

Figure 1. Map showing the locations of the earthquakes (circles) and E. Kazakh explosions (squares) used in this study. The location of station WMQ is also indicated. The two events indicated by 89043b and 86348 in solid circles are within 20° azimuth from WMQ.

2.0 DATA ANALYSIS

Seismic event discrimination based on spectral signatures has been applied to regional data recorded at stations of the CDSN during 1987. The data base consisted of 26 explosions and 101 earthquakes (Table 1) recorded at the station WMQ of the CDSN with paths traversing the East Kazakh and Tien Shan regions. The locations of the station WMQ and of the seismic events are shown in Figure 1. In this study, the regional phases *Pn, Pg*, and *Lg* are emphasized in the analysis. Data are retrieved from the vertical component of the short-period and broad-band channel of the CDSN station. In order to study the frequency distribution of the various phases, we have performed a band-pass filtering of the data (Fig. 2a). For this, we have used an infinite impulse response 3-pole butterworth filter in order to be able to band-pass the entire waveform. The filtered, short-period data indicate that there are *Pg*-phase signals above the noise level at a pass-band of as high as 16-20 Hz, whereas *Lg*-phase signals are observed up to the 8-16 Hz pass-band for explosions, and there is much lower frequency energy for earthquakes.

Pg and *Lg* arrival times are determined and windowed from 2 seconds before the picked arrival times for a total of 10 and 50 seconds respectively (Figure 2b). The noise is determined as 20 seconds before the arrival of each phase. A 10% cosine taper is applied to the beginning and end of the segmented waveforms. The windowed data segments are Fourier transformed into the spectral domain. The spectral ratios are obtained by taking the geometric means at a particular pass-band for each phase and then dividing by the means of each other phase. Only data with a signal-to-noise power ratio of over 2 for both *Pg* and *Lg* phases are used in the study. Spectral ratios are obtained for frequency bands 0.2-0.5 Hz, 0.5-2 Hz, 2-4 Hz, 4-6 Hz, 6-8 Hz for the broad-band data; for the short-period data, spectral ratios are obtained for frequency bands 2-4 Hz, 4-6 Hz, 6-8 Hz, 8.-16 Hz, 16-24 Hz. Time-domain measurements have been performed for a few test cases and have been found to produce a negligible difference from those obtained from the spectral method.

TABLE 1

EXPLOSIONS

EVENT	Mon	DDYEARDOY	Origin time	Lat	Lon	Dep	Mb	Dist
87071a	Mar	12,1987071	01:57:17.2	49.94	78.82	000	5.5	8.6
87093a	Apr	03,1987093	01:17:08.0	49.93	78.83	000	6.2	8.6
87157a	Jun	06,1987157	02:37:07.0	49.86	78.11	000	5.3	8.9
87171	Jun	20,1987171	00:53:04.8	49.91	78.73	000	6.1	8.6
87198a	Jul	17,1987198	01:17:07.0	49.80	78.11	000	5.8	8.9
87214a	Aug	02,1987214	00:58:06.8	49.88	78.92	000	5.9	8.5
87319a	Nov	15,1987319	03:31:06.7	49.87	78.79	000	6.0	8.6
87347a	Dec	13,1987347	03:21:04.8	49.99	78.84	000	6.1	8.6
87354	Dec	20,1987354	02:55:06.7	49.83	78.00	000	4.8	9.0
87361a	Dec	27,1987361	03:05:04.7	49.86	78.76	000	6.1	8.6
88037a	Feb	06,1988037	04:19:07.5	49.80	78.06	000	4.8	8.9
88037a	Feb	06,1988037	04:19:11.1	49.80	78.06	000	4.8	8.9
88044	Feb	13,1988044	03:05:05.9	49.95	78.91	000	6.1	8.6
88094	Apr	03,1988094	01:33:05.8	49.92	78.95	000	6.1	8.5
88125	May	04,1988125	00:57:06.8	49.93	78.77	000	6.1	8.6
88166	Jun	14,1988166	02:27:06.4	50.05	79.01	000	5.0	8.6
88258	Sep	14,1988258	03:59:57.4	49.82	78.80	000	6.1	8.6
88270	Sep	26,1988270	07:45:00.0	49.90	78.80	000	0.0	8.6
88292	Oct	18,1988292	03:40:06.4	49.87	78.08	000	4.9	8.9
88317	Nov	12,1988317	03:30:03.7	50.08	78.99	000	5.3	8.6
88328	Nov	23,1988328	03:57:06.7	49.82	78.07	000	5.3	8.9
88352	Dec	17,1988352	04:18:06.9	49.89	78.93	000	5.9	8.5
89043	Feb	12,1989043	04:15:06.8	49.93	78.74	000	5.9	8.7
89048	Feb	17,1989048	04:01:06.9	49.87	78.08	000	5.0	8.9
89189	Jul	08,1989189	03:46:57.6	49.87	78.82	000	5.6	8.6
89245	Sep	02,1989245	04:16:57.2	50.02	79.05	000	5.0	8.6

EARTHQUAKES (all depths)

EVENT	Mon	DDYEARDOY	Origin time	Lat	Lon	Dep	Mb	Dist
86249	Sep	06,1986249	15:31:01.8	36.41	71.33	084	5.0	14.5
86253b	Sep	10,1986253	13:46:15.3	36.89	76.81	033	4.8	10.8
86256b	Sep	13,1986256	14:14:54.3	36.44	70.77	200	4.9	14.9
86260	Sep	17,1986260	12:08:09.4	37.29	71.73	120	5.5	13.8
86274	Oct	01,1986274	11:11:42.1	41.68	76.86	010	4.8	8.3
86276	Oct	03,1986276	07:48:37.0	39.47	75.29	014	4.7	10.2
86277a	Oct	04,1986277	04:29:57.1	42.40	84.63	033	4.0	2.7
86308	Nov	04,1986308	16:19:15.1	50.88	89.27	010	5.3	7.1
86316b	Nov	12,1986316	11:32:51.5	44.81	94.04	033	4.3	4.7
86324a	Nov	20,1986324	02:40:25.6	42.04	84.39	050	4.6	3.0
86339	Dec	05,1986339	10:34:34.0	39.87	77.21	033	4.4	8.8
86348	Dec	14,1986348	03:19:16.7	47.31	83.31	033	5.0	4.7

87005	Jan 05,1987005	22:52:46.5	41.96	81.32	017	5.9	5.0
87024a	Jan 24,1987024	08:09:21.3	41.53	79.32	029	5.9	6.6
87024e	Jan 24,1987024	08:59:33.8	41.25	79.20	033	4.7	6.8
87024g	Jan 24,1987024	13:40:40.3	41.44	79.25	033	5.2	6.7
87024i	Jan 24,1987024	14:45:57.3	41.38	79.51	033	4.4	6.5
87025a	Jan 25,1987025	06:10:56.3	41.35	79.30	033	4.5	6.7
87025b	Jan 25,1987025	22:49:12.2	41.34	79.30	033	4.5	6.7
87026b	Jan 26,1987026	05:28:40.8	41.32	79.20	033	4.5	6.8
87028a	Jan 28,1987028	00:01:39.9	41.33	79.21	033	4.5	6.7
87028b	Jan 28,1987028	12:12:15.9	45.36	96.14	033	5.1	6.2
87037	Feb 06,1987037	21:22:15.2	36.89	69.55	033	4.3	15.5
87045	Feb 14,1987045	23:03:13.9	41.33	79.51	033	4.7	6.5
87054b	Feb 23,1987054	22:31:05.7	41.36	79.31	033	4.6	6.7
87060c	Mar 01,1987060	17:59:10.0	49.78	102.75	024	4.8	11.9
87062b	Mar 03,1987062	09:41:33.6	41.29	79.30	033	5.1	6.7
87094	Apr 04,1987094	17:45:13.3	42.45	79.95	033	4.1	5.8
87120a	Apr 30,1987120	05:17:37.0	39.76	74.57	008	5.7	10.6
87125c	May 05,1987125	15:40:47.5	36.48	70.67	202	5.8	14.9
87130d	May 10,1987130	20:19:33.1	44.29	79.74	033	4.5	5.8
87159b	Jun 08,1987159	13:30:32.8	39.75	74.62	010	5.1	10.6
87181	Jun 30,1987181	01:05:29.6	36.59	71.07	243	4.8	14.6
87217a	Aug 05,1987217	10:24:21.0	41.32	82.13	033	4.8	4.8
87218	Aug 06,1987218	09:06:48.3	38.07	72.98	142	4.8	12.5
87230	Aug 18,1987230	02:14:14.2	36.45	71.11	207	4.9	14.7
87246b	Sep 03,1987246	09:08:11.7	38.78	75.29	033	4.8	10.6
87259	Sep 16,1987259	17:57:26.4	52.09	95.70	033	4.8	9.9
87261b	Sep 18,1987261	21:58:41.5	47.02	89.66	033	5.3	3.5
87263a	Sep 20,1987263	03:54:06.5	42.92	77.62	041	4.6	7.4
87276b	Oct 03,1987276	11:00:05.2	36.45	71.44	095	5.9	14.4
87289c	Oct 16,1987289	18:30:51.3	44.20	82.84	056	4.7	3.5
87351b	Dec 17,1987351	12:17:25.6	41.94	83.20	052	5.1	3.8
87355a	Dec 21,1987355	04:28:23.5	38.70	70.67	015	4.8	13.8
87356a	Dec 22,1987356	00:16:39.0	41.36	89.64	021	5.9	2.8
87358b	Dec 24,1987358	18:28:29.2	52.98	107.73	033	4.5	16.1
87358c	Dec 24,1987358	19:29:32.9	52.97	107.61	033	4.4	16.0
88002b	Jan 02,1988002	22:02:36.0	40.06	77.34	033	4.9	8.6
88005a	Jan 05,1988005	06:23:14.7	38.06	74.03	165	4.9	11.8
88006c	Jan 06,1988006	15:31:10.4	39.66	75.48	012	5.1	10.0
88009	Jan 09,1988009	03:55:05.3	39.09	71.50	033	5.4	13.0
88013	Jan 13,1988013	21:23:11.8	36.45	70.85	192	4.8	14.8
88017	Jan 17,1988017	03:36:05.0	36.11	70.80	116	4.9	15.1
88018	Jan 18,1988018	09:55:40.7	36.43	70.51	211	4.9	15.1
88019	Jan 19,1988019	02:29:16.7	36.44	70.84	198	4.9	14.8
88022	Jan 22,1988022	18:48:10.8	41.99	79.52	033	4.6	6.3
88024a	Jan 24,1988024	16:49:22.1	41.44	79.36	033	4.8	6.6
88039	Feb 08,1988039	17:49:19.8	43.73	83.76	010	4.3	2.9

88061a	Mar	01,1988061	15:45:39.1	40.19	77.64	062	4.2	8.3
88075b	Mar	15,1988075	15:55:24.3	42.21	75.51	033	4.5	9.1
88085a	Mar	25,1988085	02:07:55.8	44.71	79.60	033	4.5	5.9
88086b	Mar	26,1988086	22:58:42.8	38.31	73.23	121	5.7	12.2
88092b	Apr	01,1988092	01:27:16.0	47.53	89.64	010	4.6	4.0
88114a	Apr	23,1988114	05:42:59.7	36.56	73.01	038	4.8	13.4
88123a	May	02,1988123	02:13:25.6	40.10	82.23	010	4.9	5.5
88146a	May	25,1988146	00:05:23.4	40.63	77.76	034	4.9	8.0
88146b	May	25,1988146	18:21:58.0	42.01	85.69	022	5.2	2.3
88146c	May	25,1988146	22:52:55.4	46.14	98.98	033	4.1	8.3
88155c	Jun	03,1988155	18:26:06.7	36.26	70.70	130	5.1	15.0
88156b	Jun	04,1988156	07:24:22.0	55.94	113.09	033	4.8	20.2
88160	Jun	08,1988160	02:16:19.1	40.27	77.76	010	4.4	8.2
88164a	Jun	12,1988164	07:17:07.1	38.84	74.72	025	4.5	10.9
88169	Jun	17,1988169	13:30:43.9	42.97	77.51	024	5.3	7.5
88171	Jun	19,1988171	22:21:02.0	38.40	73.58	131	4.5	11.9
88182c	Jun	30,1988182	15:25:15.5	50.23	91.14	033	5.0	6.8
88202	Jul	20,1988202	06:20:50.7	37.02	72.92	035	5.5	13.1
88205c	Jul	23,1988205	07:38:09.9	48.72	90.51	018	5.5	5.3
88213	Jul	31,1988213	22:33:30.8	36.63	71.23	092	4.5	14.5
88214	Aug	01,1988214	23:39:18.5	36.50	70.75	193	4.3	14.9
88216a	Aug	03,1988216	05:43:14.8	36.48	70.97	202	5.4	14.7
88216b	Aug	03,1988216	12:04:17.3	36.44	70.93	206	4.7	14.8
88219d	Aug	06,1988219	09:03:21.9	36.49	71.06	194	6.0	14.7
88223a	Aug	10,1988223	10:59:05.2	36.98	71.62	126	4.8	14.0
88223b	Aug	10,1988223	20:29:48.8	36.50	71.14	069	4.7	14.6
88224	Aug	11,1988224	05:00:09.7	37.50	70.01	033	5.1	14.8
88225	Aug	12,1988225	18:58:40.3	40.32	73.48	033	5.2	11.1
88230	Aug	17,1988230	14:56:31.3	39.31	72.34	030	4.9	12.3
88253a	Sep	09,1988253	21:12:36.2	36.45	71.37	101	5.4	14.5
88253b	Sep	09,1988253	21:19:34.1	36.37	71.98	199	4.2	14.1
88267b	Sep	23,1988267	04:46:40.4	39.55	74.55	033	5.3	10.7
88269a	Sep	25,1988269	19:41:11.3	36.22	70.62	159	4.7	15.1
88269c	Sep	25,1988269	21:28:04.8	36.40	70.73	213	5.5	14.9
88270b	Sep	26,1988270	07:17:00.1	36.31	71.38	107	5.6	14.6
88277	Oct	03,1988277	00:24:49.8	38.68	70.77	033	4.8	13.7
88280a	Oct	06,1988280	13:10:54.4	39.60	74.40	033	5.0	10.8
88280b	Oct	06,1988280	18:22:55.5	39.59	74.36	033	4.9	10.8
88295a	Oct	21,1988295	01:55:20.3	39.75	72.28	033	4.4	12.2
88295b	Oct	21,1988295	18:10:48.1	36.66	71.31	188	4.2	14.4
88300	Oct	26,1988300	02:15:12.8	36.49	70.87	220	5.0	14.8
88332a	Nov	27,1988332	01:16:21.7	36.04	70.54	092	4.8	15.3
89043b	Feb	12,1989043	23:49:17.0	51.00	84.17	033	4.6	7.6

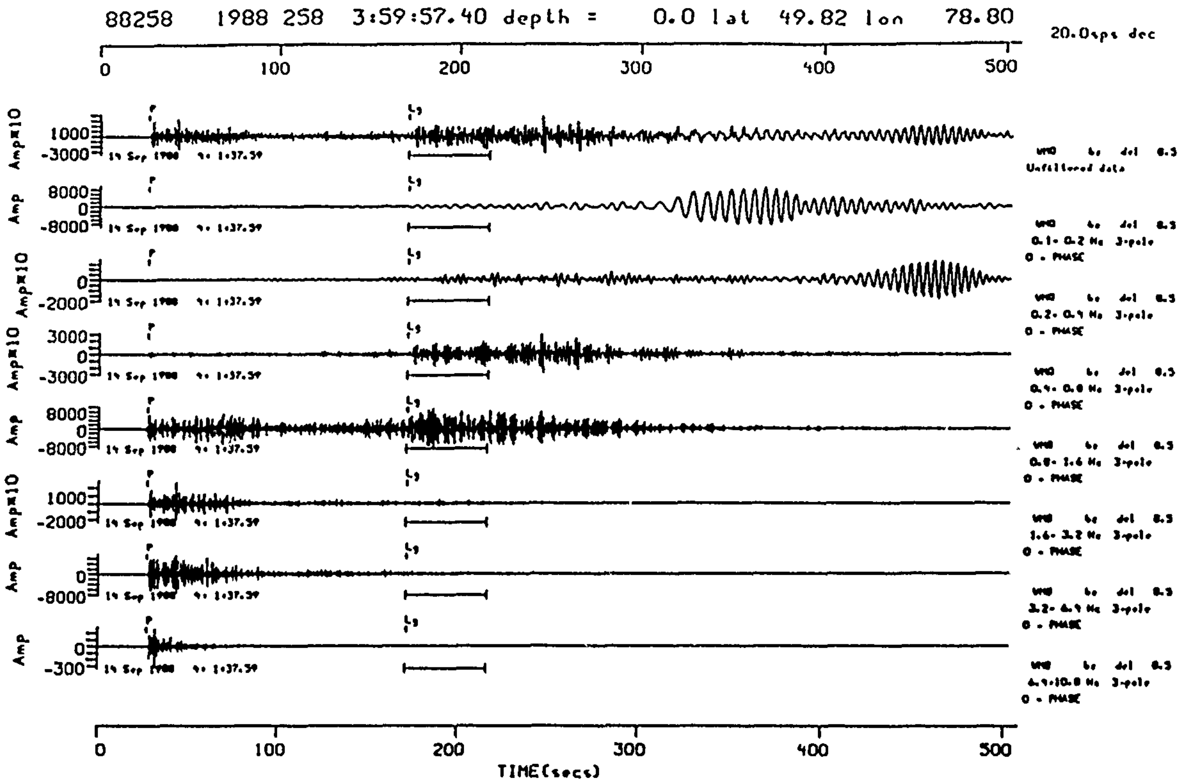

Figure 2a. Band pass filtering of an explosion in E. Kazakh recorded at WMQ. An infinite impulse response 3-pole butterworth filter is used. The top trace is the unfiltered short-period vertical data. The frequency bands are 0.1-0.2 Hz, 0.2-0.4 Hz, 0.4-0.8 Hz, 0.8-1.6 Hz, 1.6-3.2 Hz, 3.2-6.4 Hz, and 6.4-10.0 Hz.

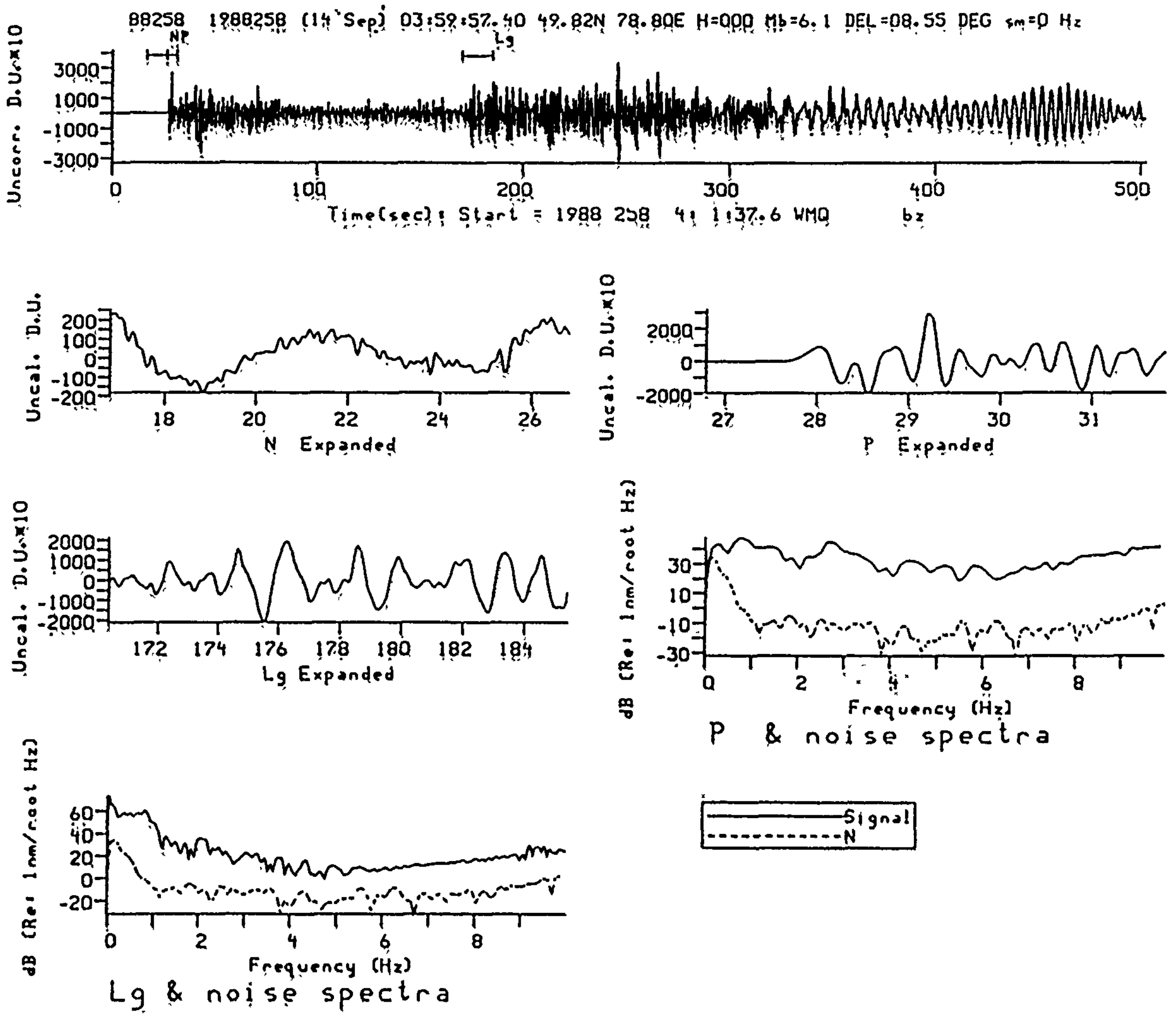

Figure 2b. Processing of Pg and Lg spectral ratio. The signal and noise level for Pg and Lg are shown in the lower two panels. Only data with a signal-noise power ratio of over 2 for both Pg and Lg are used.

3.0 RESULTS

Guided by the band-pass filtering analysis which indicates the broad-band characteristics of the seismic signals, we are able to design the spectral ratio discrimination study in the E. Kazakh/Tien Shan region with the appropriate frequency bands and phases. Three discriminants will be tested in this study. First, the spectral ratios between *Pg* and *Lg* phases will be examined for each frequency band. Second, band-ratioing between two frequency bands will be performed to *Pg* and *Lg* phases individually. Third, the ratioing between the vertical and horizontal component *Pg* and *Lg* phases will be studied. There are various parameters that may affect the analysis, and these will be studied in the phase ratioing study.

3.1 Pg and Lg Spectral Phase Ratioing

The phases that are used in the spectral phase-ratioing consist of *Pg* and *Lg*. The bandpasses used range from 1-2 Hz to 18-20 Hz for the short-period data and from 0.5-1 to 8-10 for the broad-band data. Examples of the ratios between short-period and broad-band *Pg* and *Lg* plotted against the body wave magnitudes as obtained from the NEIS for various band-passes are shown in Figures 3 and 4. It may be observed from the plots that there is distinct separation between the earthquake and explosion populations for the various passbands. The *Pg/Lg* ratios for explosions are over an order of magnitude larger than those for earthquakes. Figure 4 shows that there is no distinct difference in spectral ratios between two groups of earthquakes that traverse paths that are of different azimuths from WMQ.

Spectral ratios between *Pg* and *Lg* plotted against the frequency for the short-period and broad-band data are shown in Figures 5 and 6. For short-period data, it is observed that within the frequency range of 2 to 14 Hz, the spectral ratios between *Pg* and *Lg* phases are capable of discriminating between earthquakes and explosions. In the case of broad-band data, there is separation between earthquakes and explosions from 4 to 10 Hz. A histogram

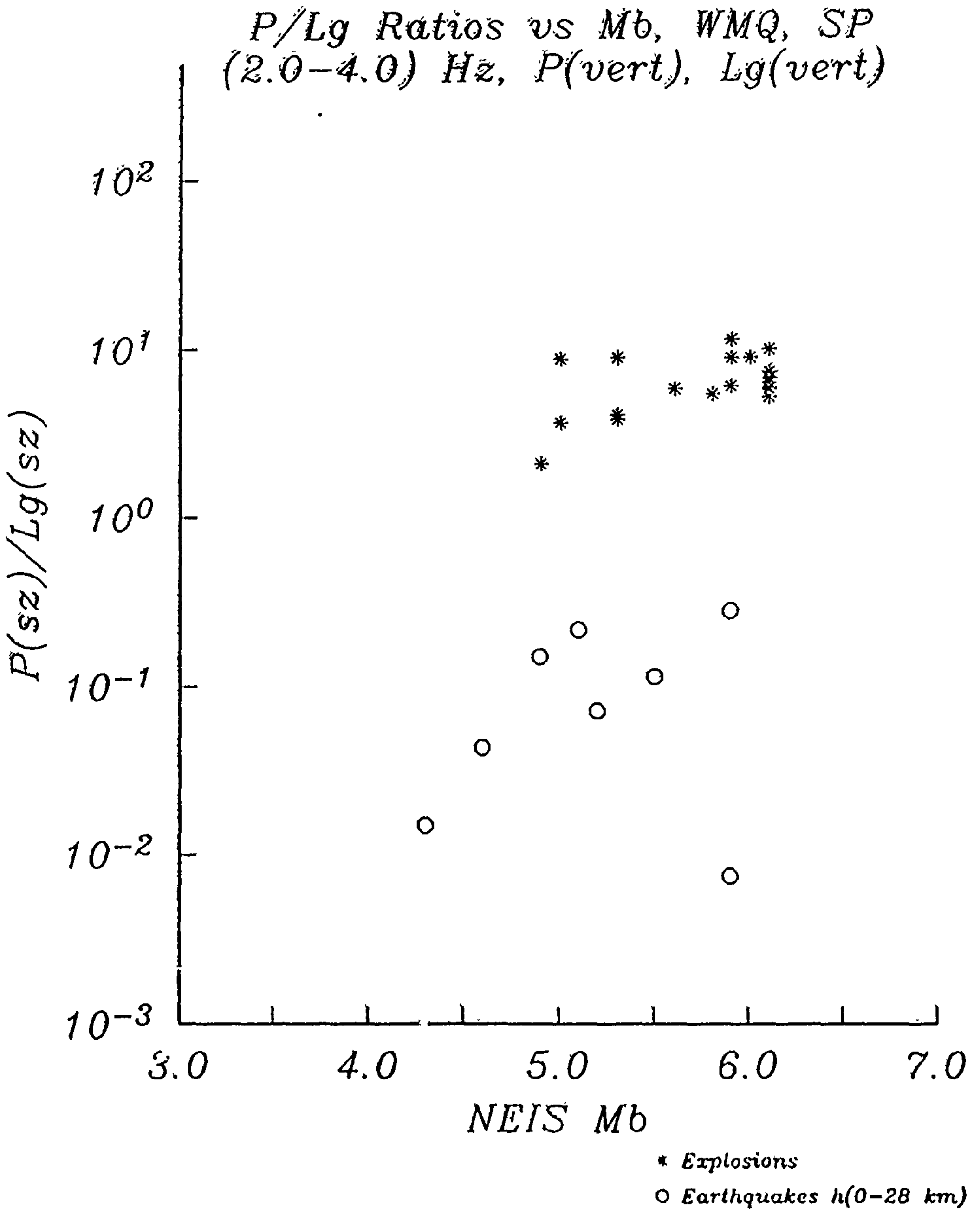

Figure 3a. Spectral ratios of *Pg/Lg* vs. mb for 2.0-4.0 Hz using short-period vertical component WMQ data. The earthquake and explosion populations are well separated.

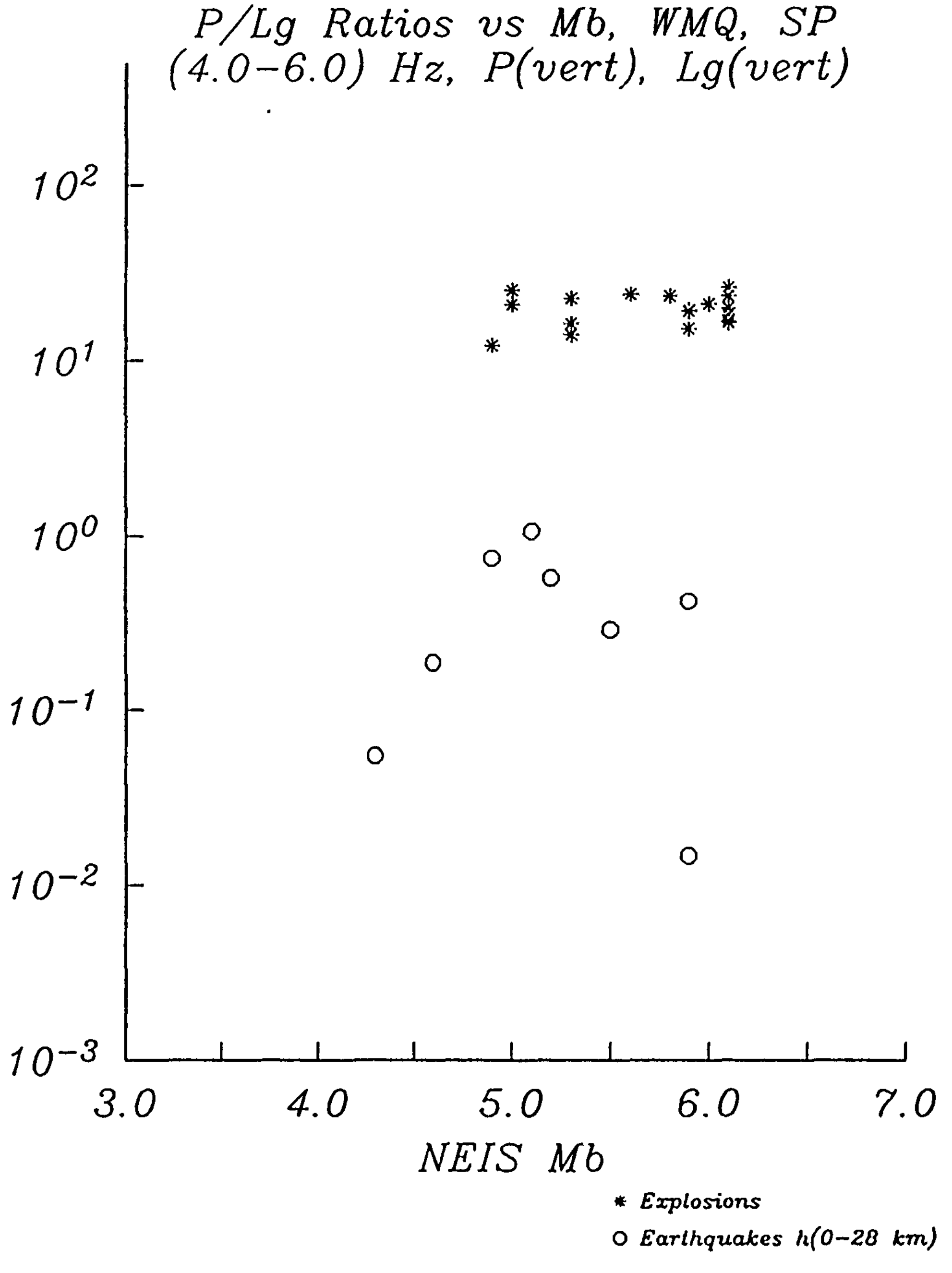

Figure 3b. Spectral ratios of *Pg/Lg vs.* mb for 4.0-6.0 Hz using short-period vertical component WMQ data. The earthquake and explosion populations are well separated.

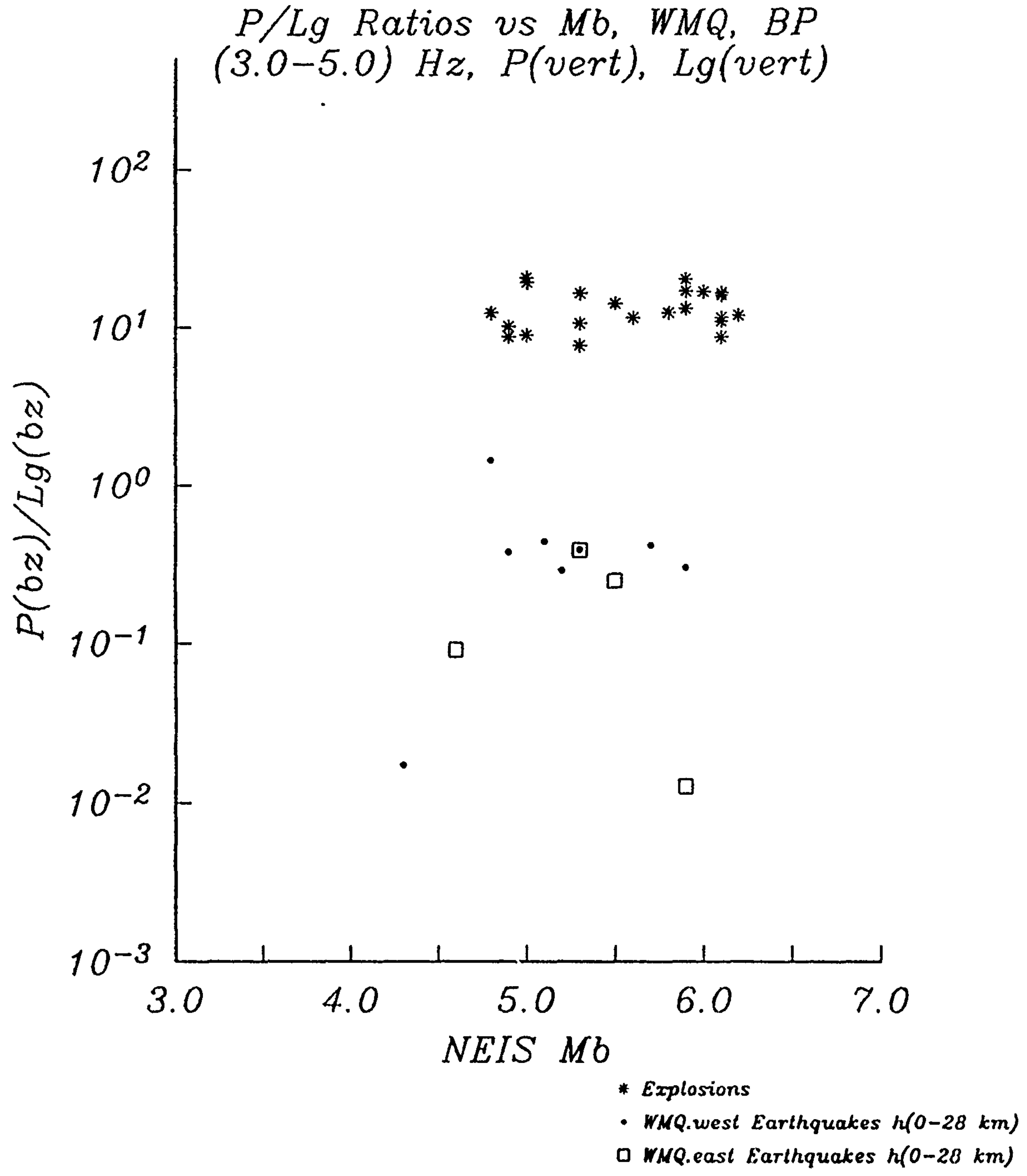

Figure 4a. Spectral ratios of *Pg/Lg vs.* mb for 3.0-5.0 Hz using broad-band vertical component WMQ data. The earthquakes are indicated as west of WMQ or east of WMQ. The earthquake and explosion populations are well separated.

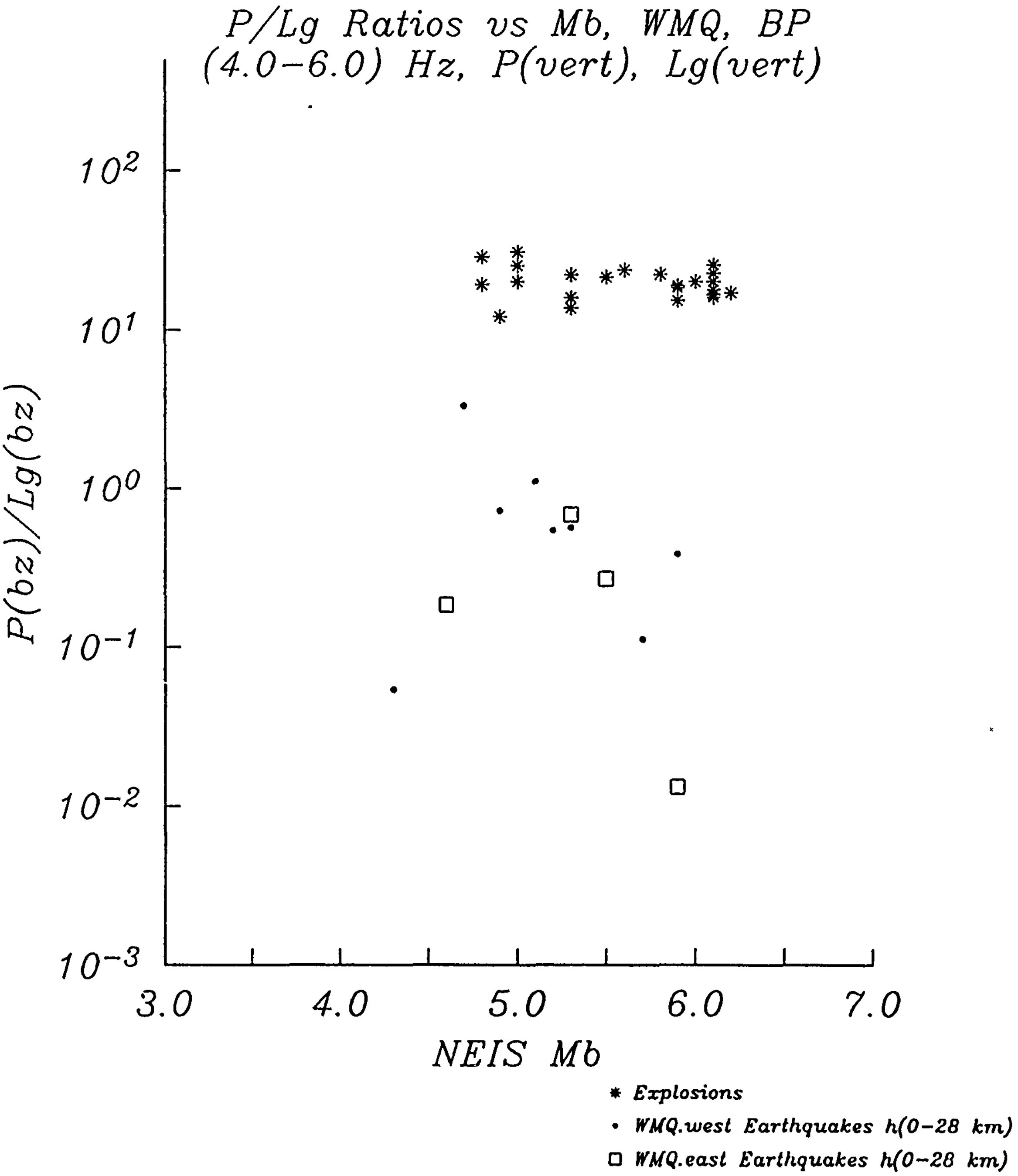

Figure 4b. Spectral ratios of *Pg/Lg vs.* mb for 4.0-6.0 Hz using broad-band vertical component WMQ data. The earthquakes are indicated as west of WMQ or east of WMQ. The earthquake and explosion populations are well separated.

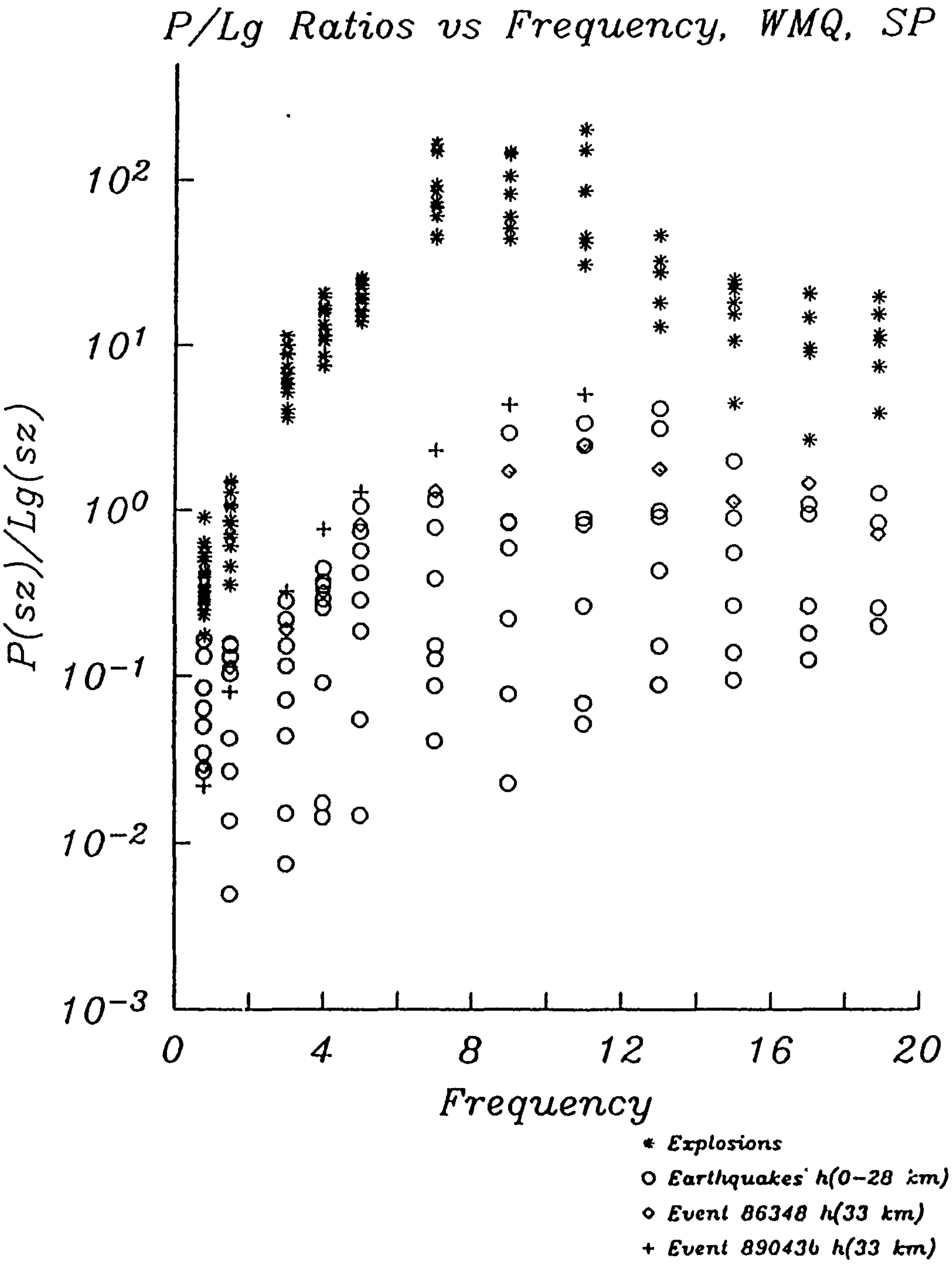

Figure 5. Plot of *Pg/Lg* spectral ratios versus frequency for earthquakes and explosions using the vertical component short-period data of WMQ. The two events within 20° azimuth from WMQ are indicated as pluses and diamonds.

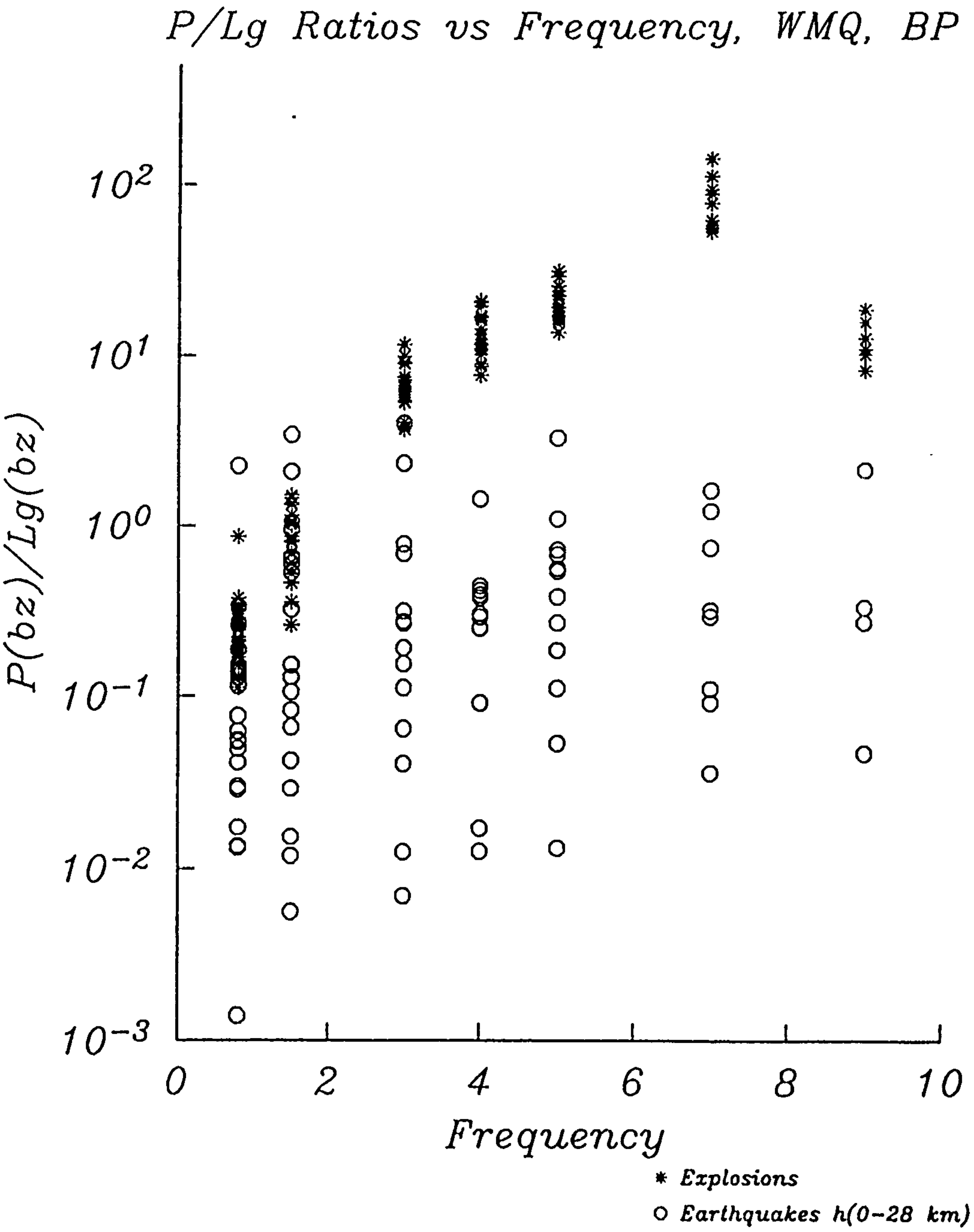

Figure 6. Plot of *Pg*/*Lg* spectral ratios versus frequency for earthquakes and explosions using the vertical component broad-band data of WMQ.

plotted in Figure 7 shows that at a center frequency of 7 Hz, the earthquake and explosion populations are distinctly separable from each other.

3.2 Pg and Lg Frequency Band-Ratioing

It has also been noticed that earthquakes and explosions have different energy content at different frequency bands. These variations in frequency bands directly contribute to the possible discriminant using regional phases. In order to further study the frequency content of the *Pg* and *Lg* phases, the spectral ratios at various frequency bands are studied to examine the spectral characteristics. Due to the broad-band nature of the CDSN stations, we are able to examine spectral ratios between widely spaced frequency bands between 1.6-2.5 Hz and 16.0-25.0 Hz using the short-period data.

Two different frequency bands of *Pg* phase, 2-4 Hz and 4-6 Hz, were ratioed using the short period data and the results are shown in Figures 8a and 8b. The earthquake and explosion populations are mixed with each other and show the same increasing trend with magnitude. A similar feature is observed for the frequency band-ratioing between 2-4 Hz and 8-10 Hz for the *Pg* phase using short-period data. The results here indicate that for larger explosions or earthquakes, the *Pg* phase appears to have less high-frequency energy. The rate of deficiency of high frequency energy with respect to magnitude remains the same for the frequency bands 4-6 Hz and 8-10 Hz.

For *Lg* phase, two similar bands of ratioing were performed and the results are shown in Figures 9a and 9b. For the frequency band-ratioing between 2-4 Hz, a pattern similar to that of the *Pg* phase is observed indicating that there is a gradual decrease of high frequency energy in the band of 4-6 Hz compared to those at 2-4 Hz as the body wave magnitude increases. Frequency band-ratioing between 2-4 Hz and 8-10 Hz show a steeper slope than the ratios studied earlier, shown in Figure 9a. This result indicates that for *Lg*, there is a more rapid depletion of energy with body wave magnitude as the frequency increases.

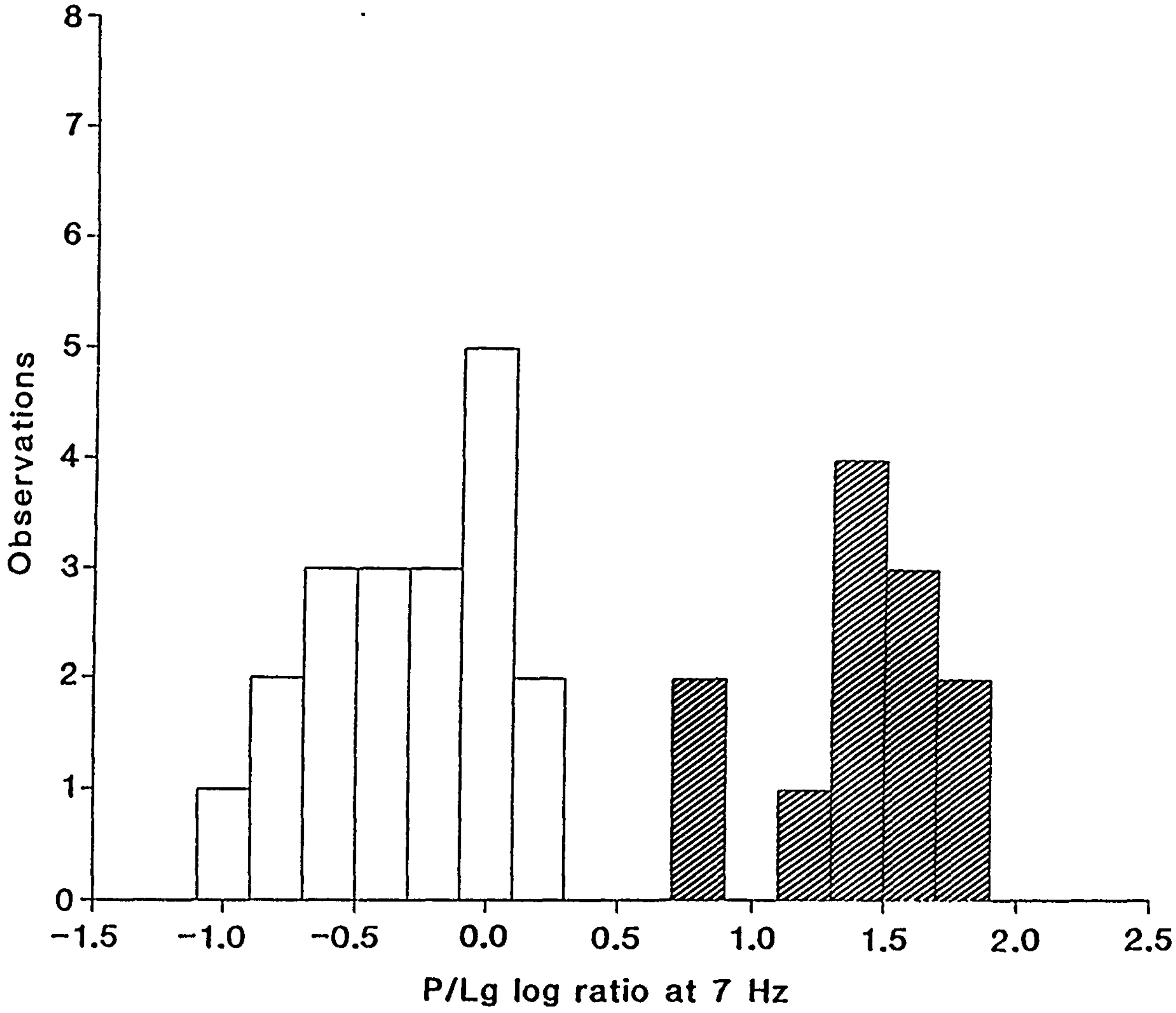

Figure 7. Histograms showing the distribution of *P/Lg* log ratio for earthquakes and explosions(shaded) at a center frequency of 7 Hz.

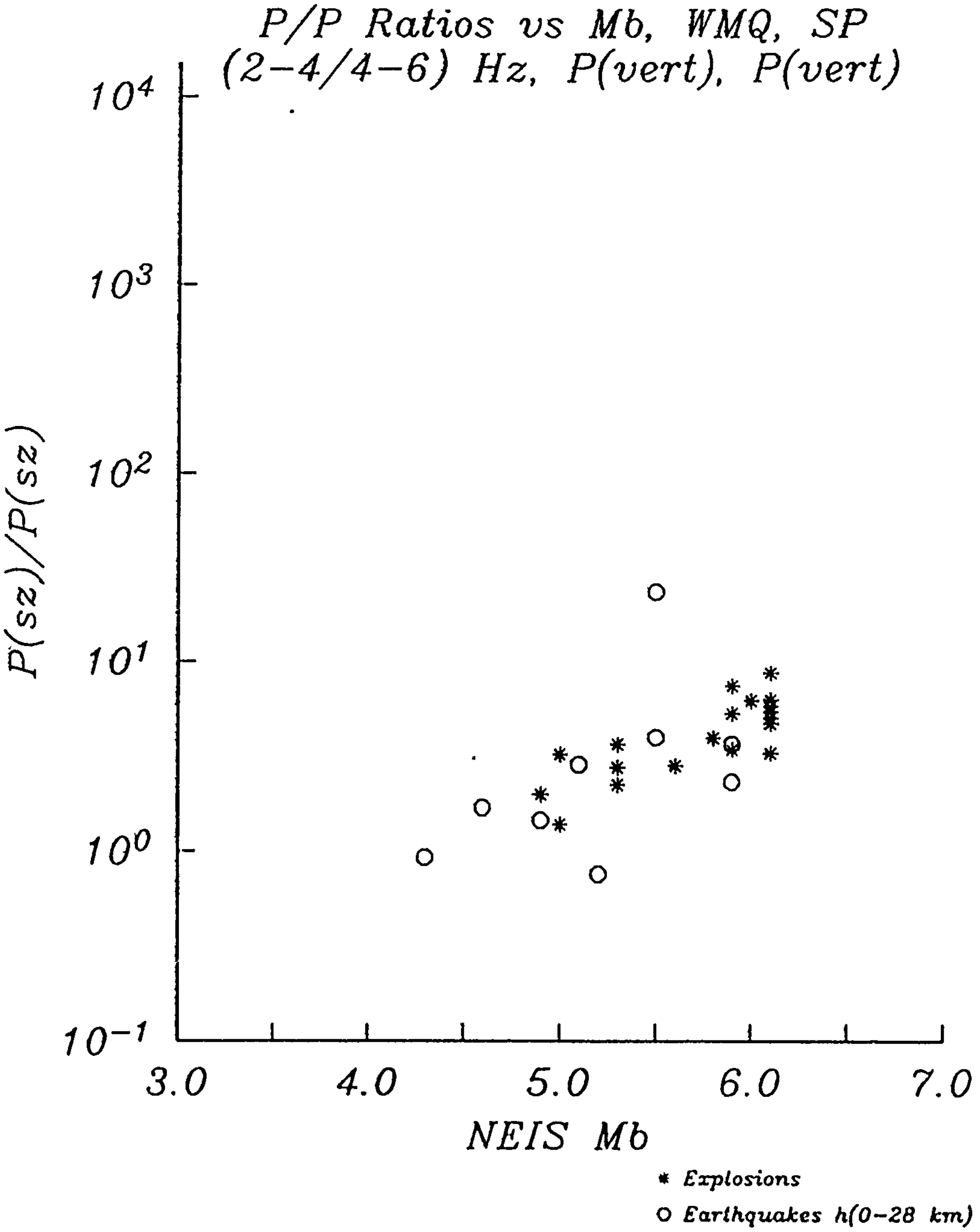

Figure 8a. Plot of *Pg*(2-4 Hz)/*Pg*(4-6 Hz) spectral ratios versus mb for earthquakes and explosions using the vertical component short-period data of WMQ.

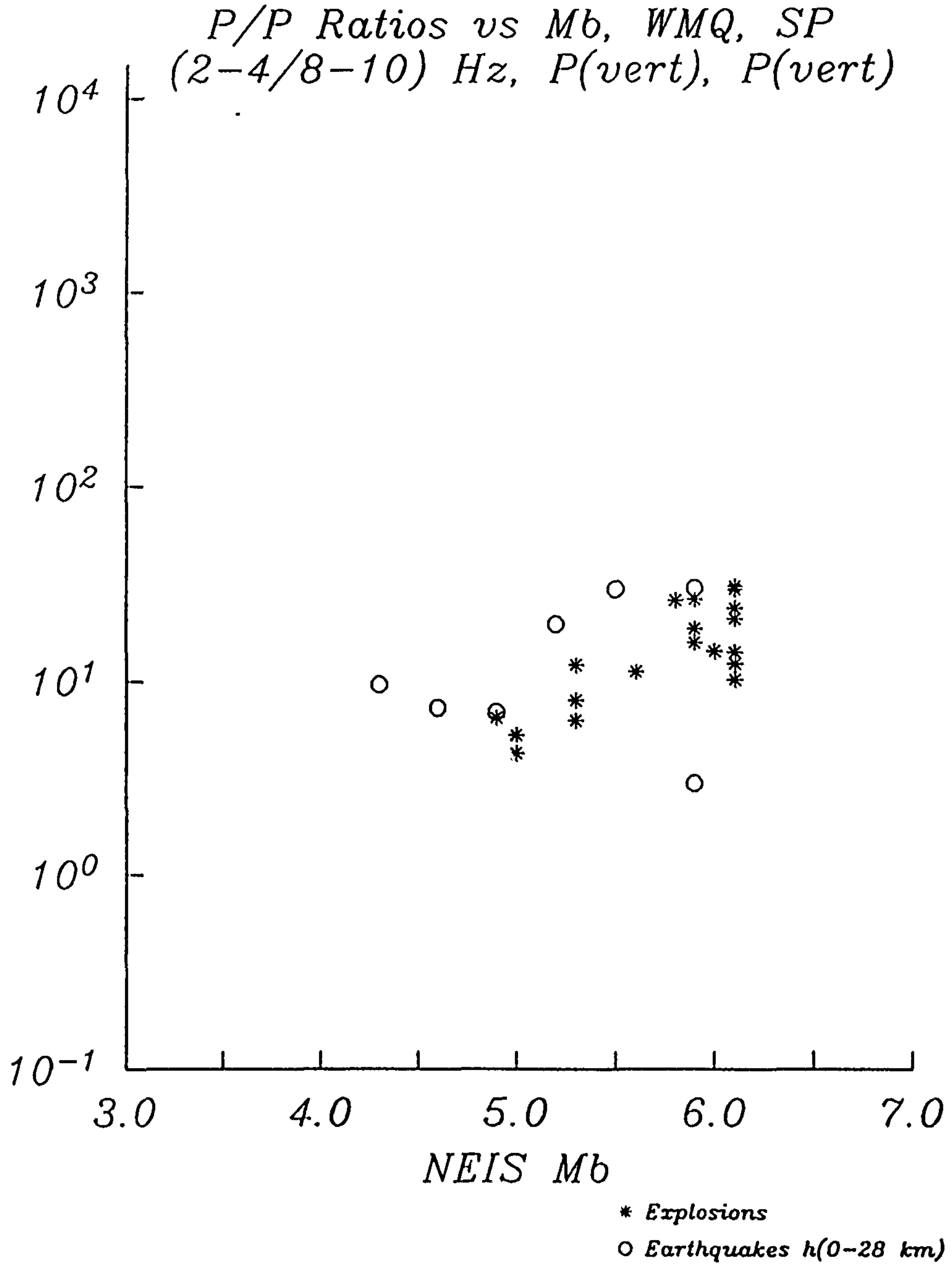

Figure 8b. Plot of *Pg*(2-4 Hz)/*Pg*(8-10 Hz) spectral ratios versus mb for earthquakes and explosions using the vertical component short-period data of WMQ.

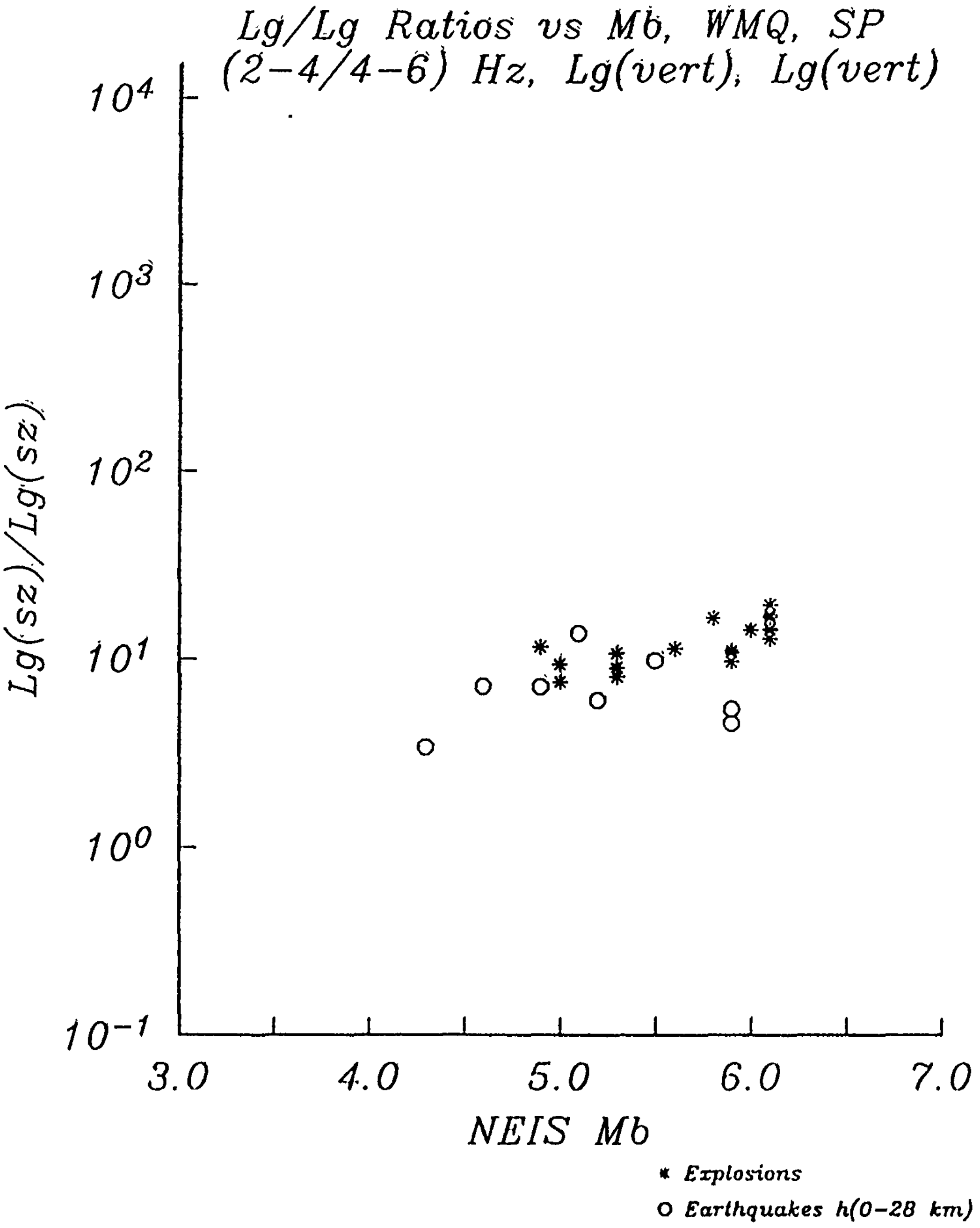

Figure 9a. Plot of *Lg*(2-4 Hz)/*Lg*(4-8 Hz) spectral ratios versus mb for earthquakes and explosions using the vertical component short-period data of WMQ.

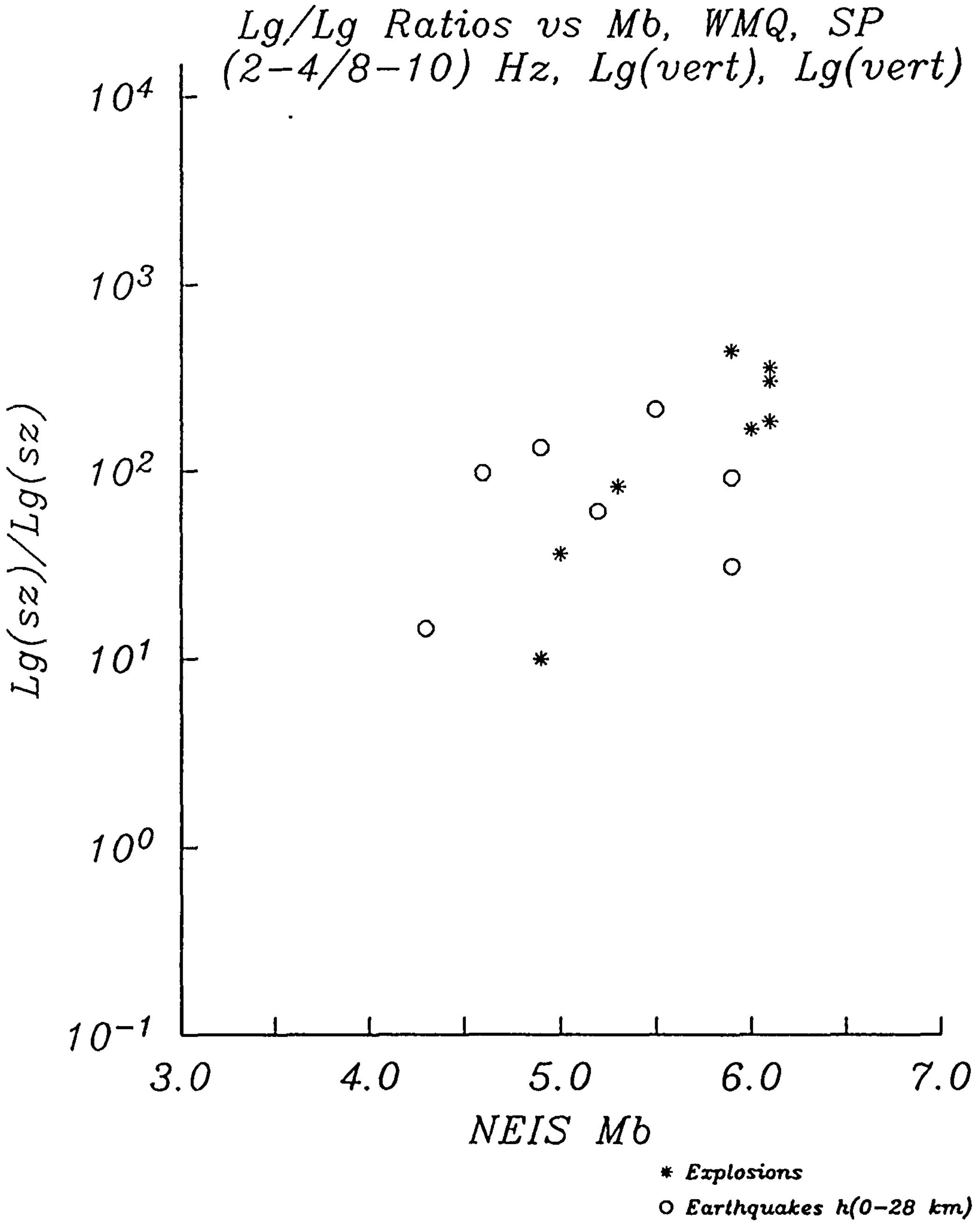

Figure 9b.Plot of Lg(2-4 Hz)/*Lg*(8-10 Hz) spectral ratios versus mb for earthquakes and explosions using the vertical component short-period data of WMQ.

3.3 Three-component Analysis

The CDSN stations are equipped with 3-component seismometers. The ratioing between the horizontal and vertical component data may guide us in determining the characteristics of the 3-component data and to evaluate whether the 3-component data may prove to be an effective discriminant. The horizontal data are first rotated to be radially and transversely polarized. The vertical component energy represents the Rayleigh-type motion, whereas the energy on the transverse component represents that of the Love-type motion.

The frequency phase ratioing between the transverse and vertical component of the data indicates that the ratios for the explosions are less than those of the earthquakes and less than unity, in particularly at frequency bands of 1.0-2.0 and 2.0-4.0 Hz, as is shown in Figures 10a and 10b. This observation is opposite from what one may expect for explosions. It is commonly believed that explosions possess less Love-type energy and therefore the ratios *Lg*(Z)/*Lg*(T) should be greater than 1. The ratios between horizontal and vertical components of *Lg* may not be used as any kind of discriminant, but the low level of the ratios for explosions is rather intriguing.

We have further tested the 3-component frequency phase-ratio between *Pg* on the vertical component and *Lg* on the transverse component at various frequency bands. In Figures 11a and 11b, the explosion and earthquake phase ratios are plotted versus body-wave magnitude, mb. Similar to the analysis in the previous section, the *Pg*(Z) to *Lg*(T) ratios for the earthquakes are lower than those of the explosions for both frequency bands between 6.0-8.0 and 4.0-6.0 Hz. The 3-component phase ratioing has produced the same result as the vertical component ratioing.

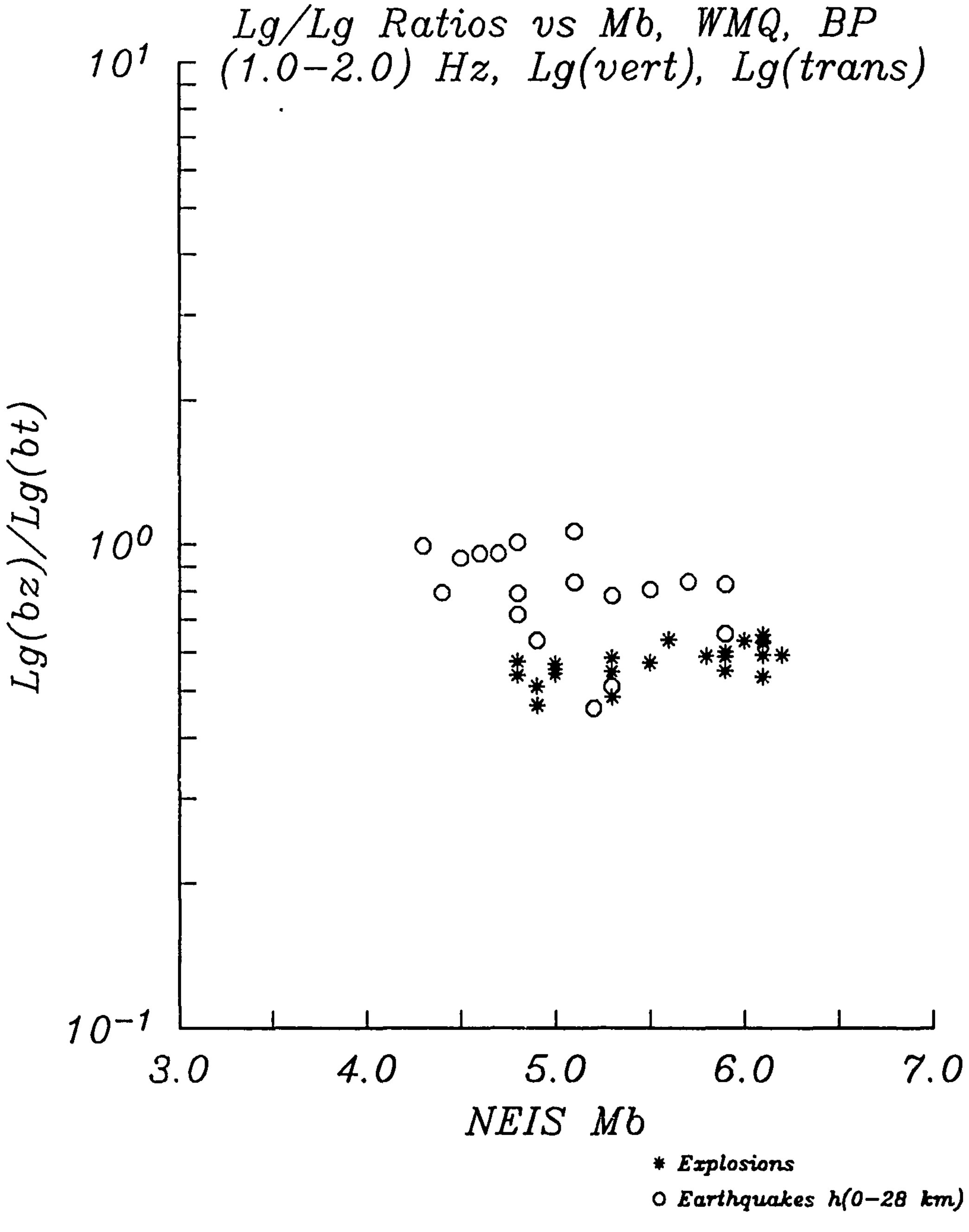

Figure 10a. Plot of *Lg*(Z)/*Lg*(T) spectral ratios at 1.0-2.0 Hz versus mb for earthquakes and explosions using the broad-band data of WMQ.

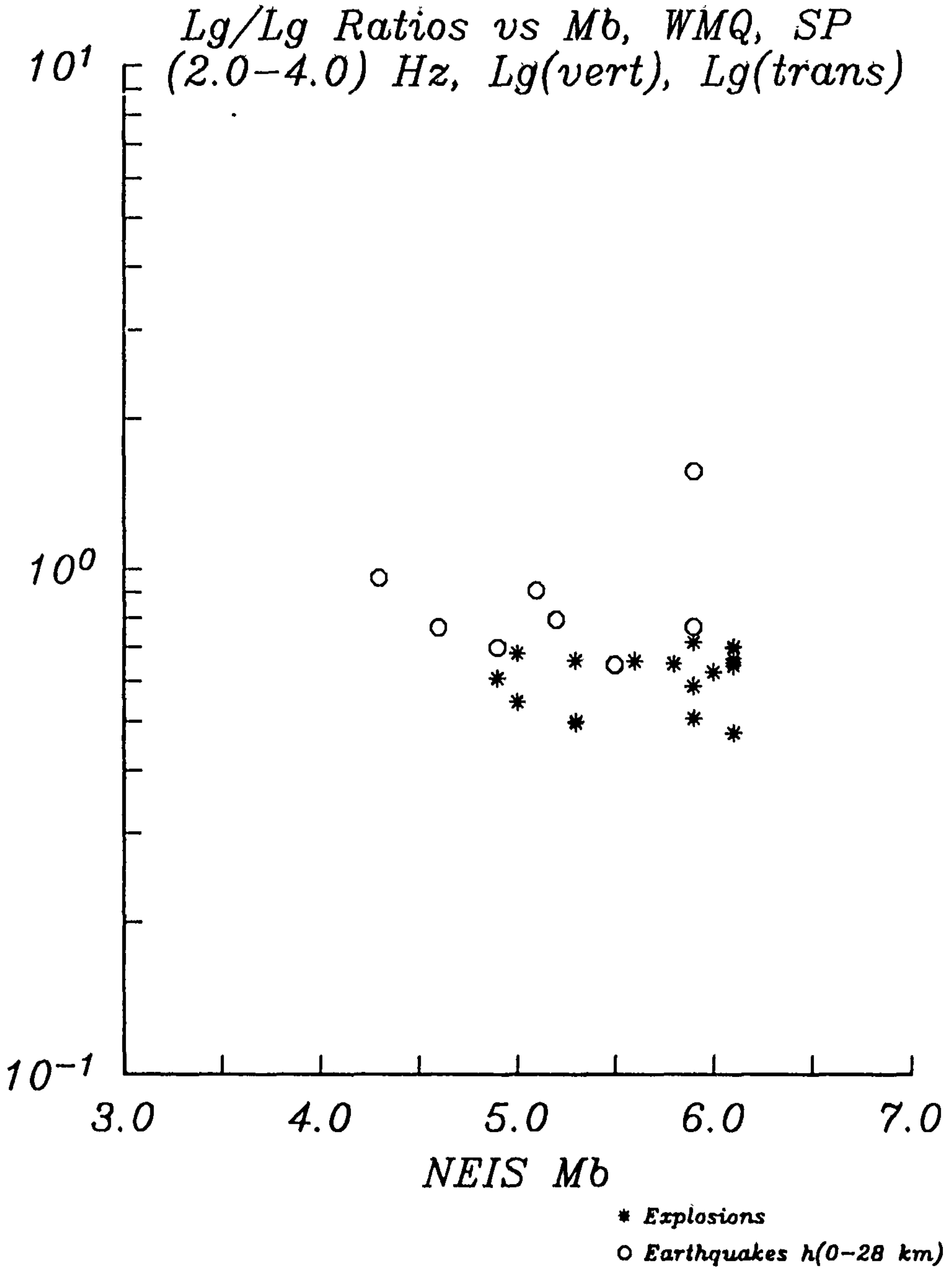

Figure 10b. Plot of *Lg*(Z)/*Lg*(T) spectral ratios at 2.0-4.0 Hz versus mb for earthquakes and explosions using the broad-band data of WMQ.

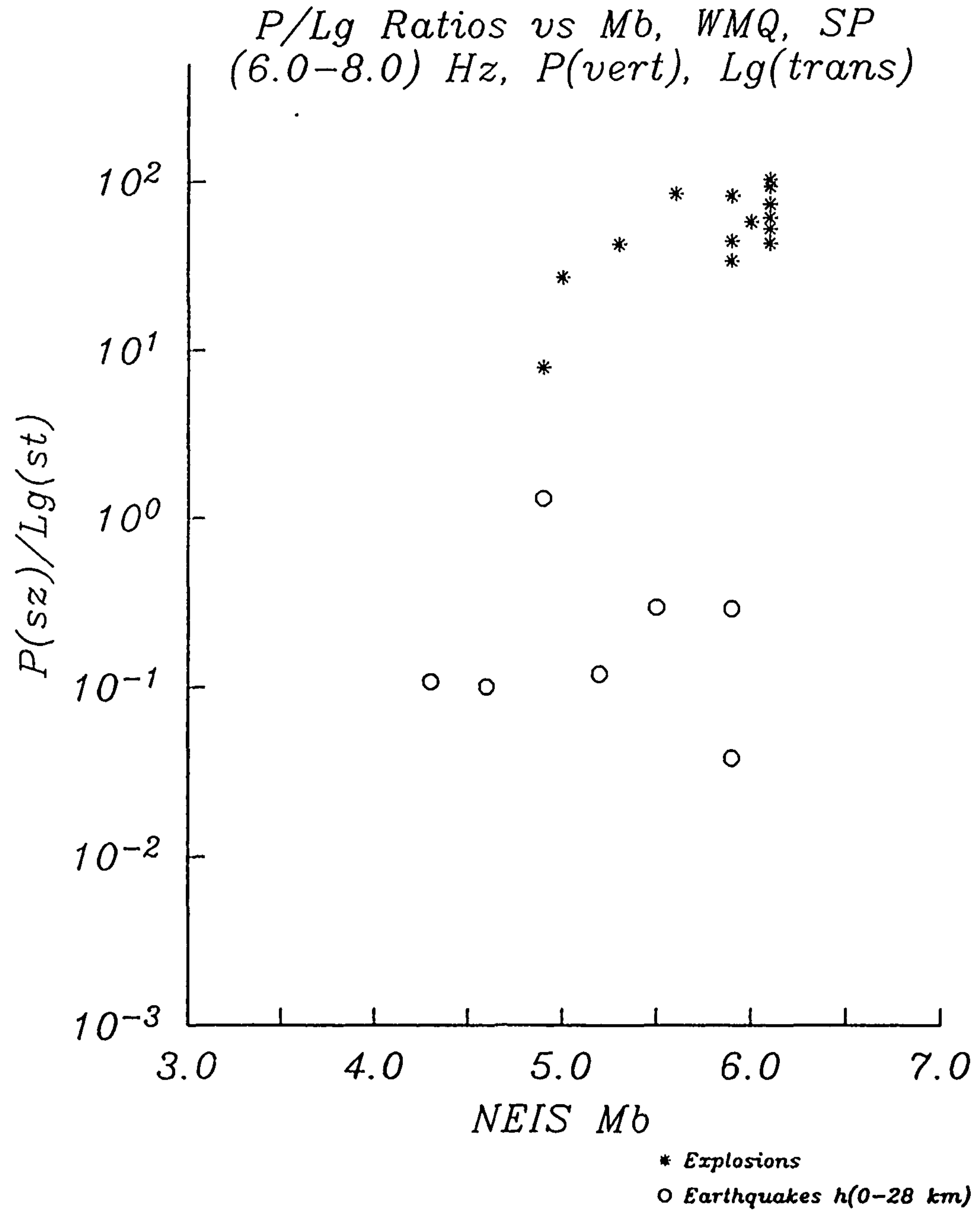

Figure 11a. Plot of *Pg*(Z)/*Lg*(T) spectral ratios at 6.0-8.0 Hz versus mb for earthquakes and explosions using the short-period data of WMQ.

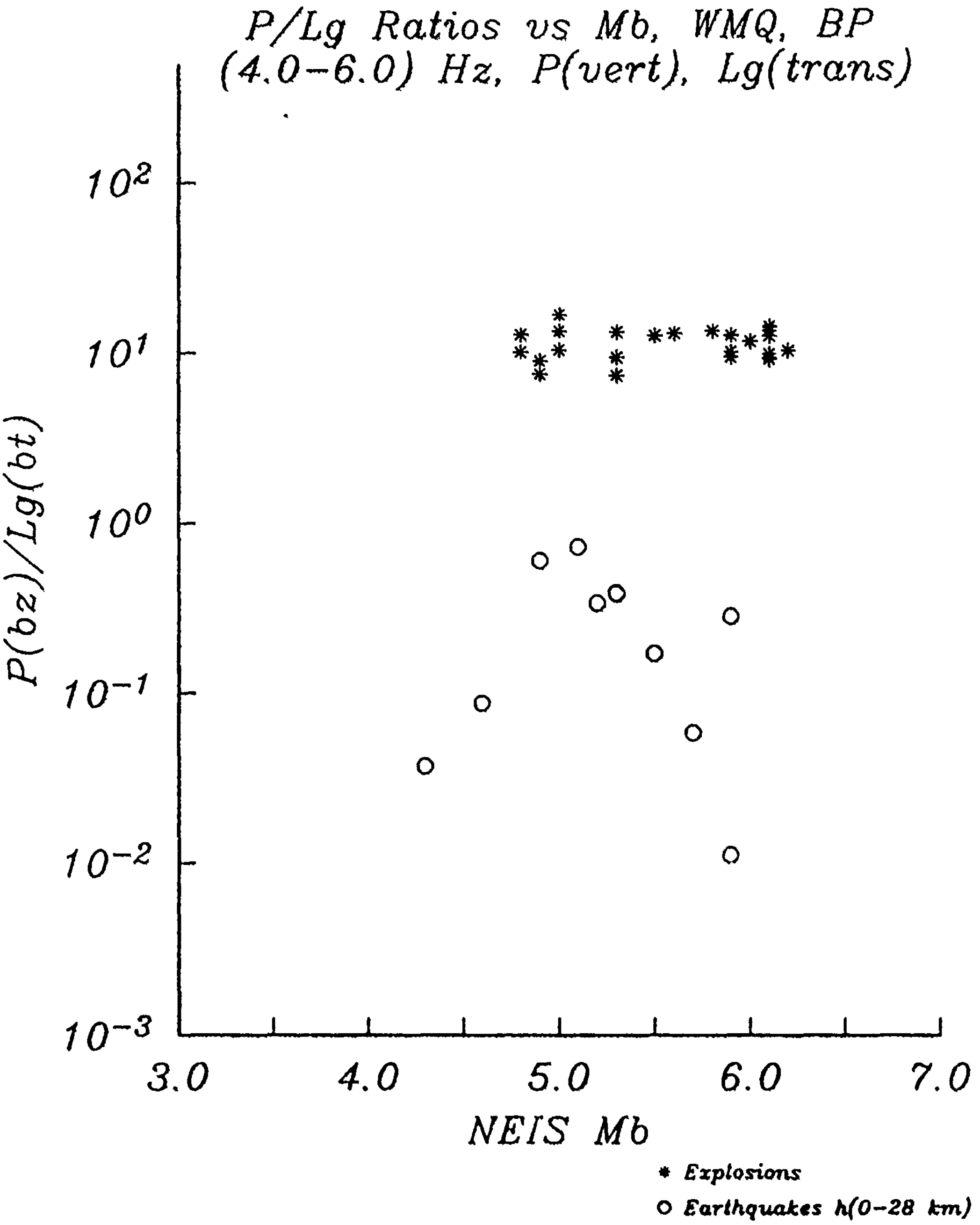

Figure 11b.Plot of *Pg*(Z)/*Lg*(T) spectral ratios at 4.0-6.0 Hz versus mb for earthquakes and explosions using the broad-band data of WMQ.

4.0 DISCUSSION

The analysis in this study has demonstrated the characteristics of spectral ratios between *Pg* and *Lg* phases for paths traversing Central Eurasia. It is observed that the results indicated the possibility of using *Pg* and *Lg* spectral ratios as a discriminant between earthquakes and explosions. Before one can be conclusive on such a discriminant, a suite of parameters need to be evaluated in terms of how they might affect the discriminant.

4.1 Depth Effect

For most of this study, the depths of the earthquakes used have been limited to less than 28 km. This limit is arbitrarily chosen to ensure that all earthquakes be of shallow focus. The gross effect of depths on the spectral ratio relationship is shown in Figures 12a and 12b. The figures indicate that the deeper focus earthquakes have a larger *Pg/Lg* spectral ratio at both the low (0.2-0.5 Hz) and the high (2.0-4.0 Hz) frequency bands. This analysis indeed shows that the depth parameters do indeed have significant effects on the *Pg/Lg* spectral ratio level. Furthermore, by plotting the spectral ratios against depth as is shown in Figure 13, it is observed that the explosion population remains well separated from the earthquakes at all depths. Frankel (1989) had demonstrated the effects of source depth on the spectral characteristics of regional phases using synthetic seismograms. Even though the depth wavelength in Frankel's study is orders of magnitude different from the above analysis, it nonetheless demonstrates the large scale effect of source depth on spectra.

4.2 Frequency Effect

It is also a goal of this study to understand the effect of frequency on the spectral ratio discriminant. Section 3.2 showed the effect of frequency band-ratioing of the *Pg* and *Lg* phases, indicating that the variations in frequency bands are too insensitive to allow the band-ratioing method to be an effective discriminant. Due to the scatter in the band-ratioing for both phases (Figures 8 and 9), it fails to provide a definite indication as to whether

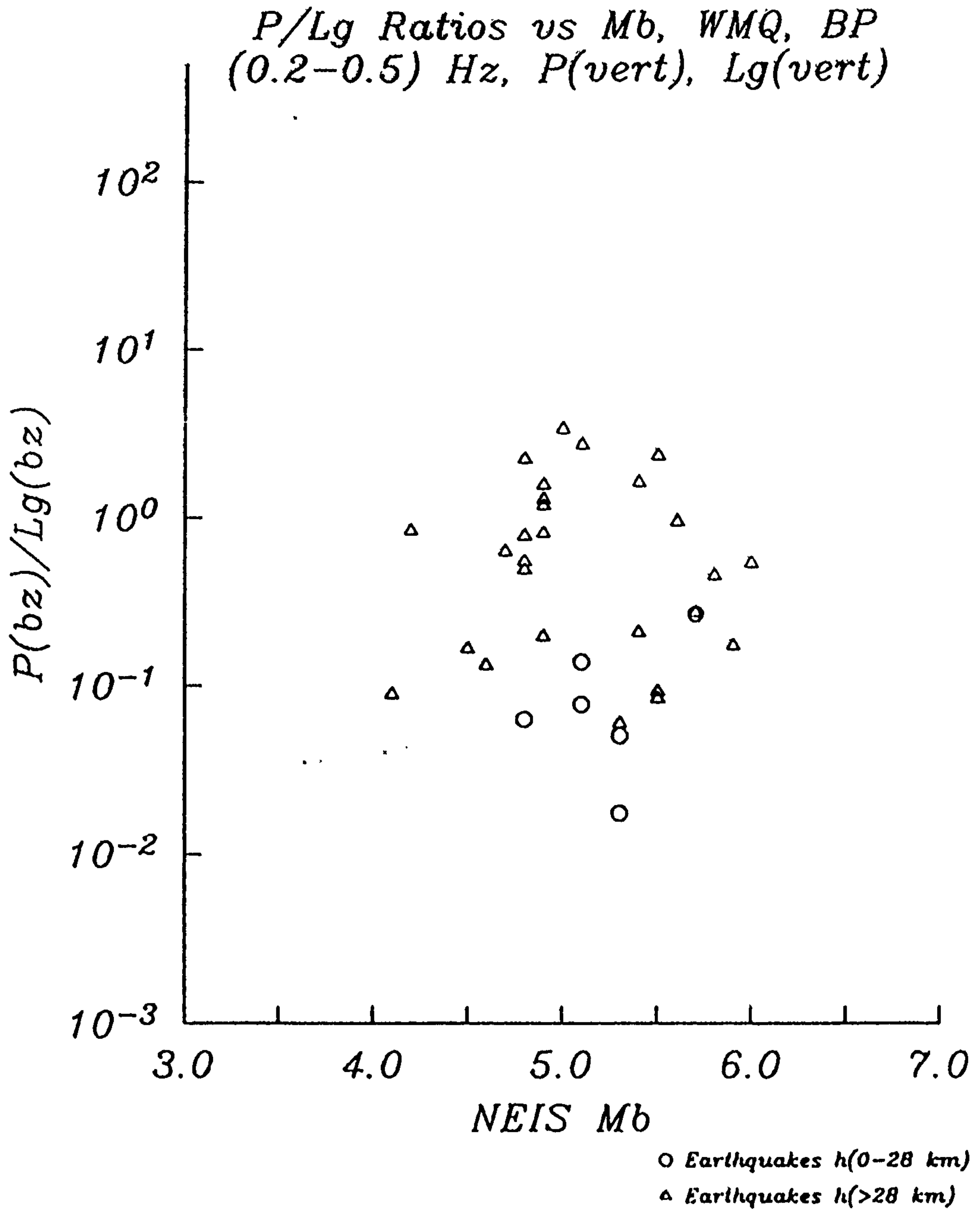

Figure 12a. Plot of *Pg/Lg* spectral ratios at 0.2-0.5 Hz versus mb for earthquakes and explosions using the vertical component broad-band data of WMQ.

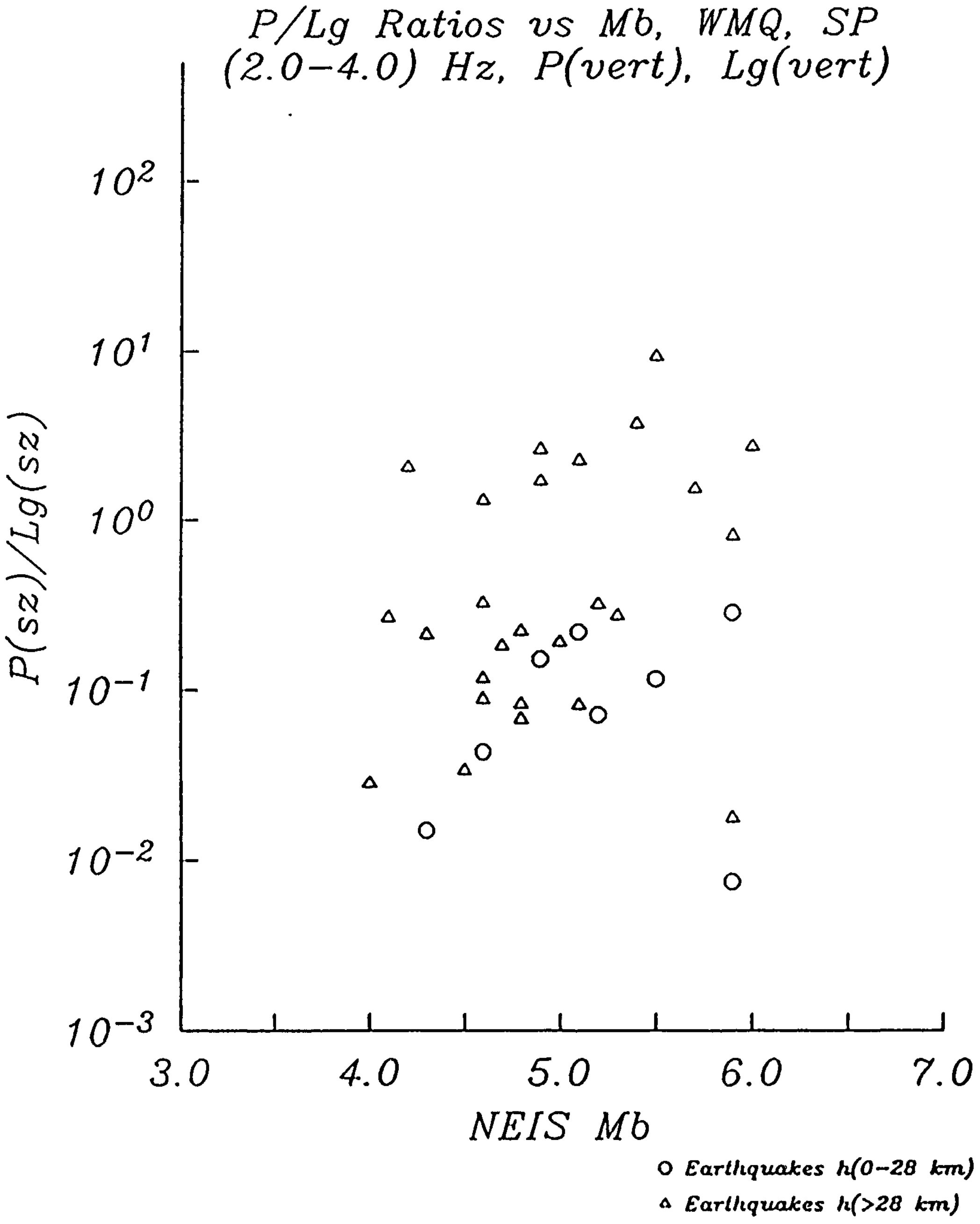

Figure 12b. Plot of *Pg/Lg* spectral ratios at 2.0-4.0 Hz versus mb for earthquakes and explosions using the vertical component short-period data of WMQ.

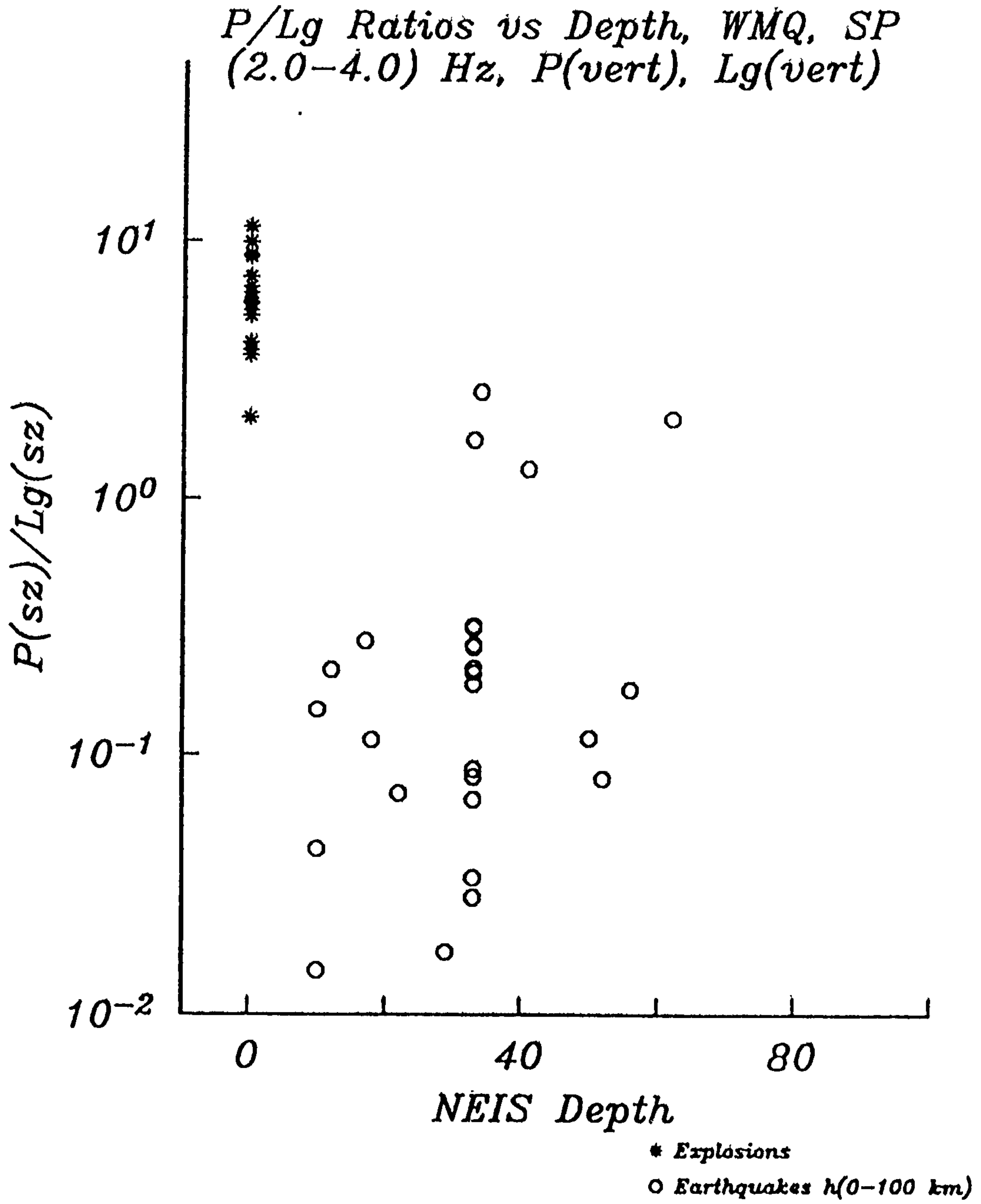

Figure 13. Plot of *Pg/Lg* spectral ratios at 2.0-4.0 Hz versus depth for earthquakes and explosions using the vertical component short-period data of WMQ.

earthquakes or explosions contain more high frequency energy for these two phases. One exception is that there is an indication that explosion *Pg* contains more high frequency energy, as is shown in Figure 8b where most explosion ratios fall below those of earthquakes. In the case of *Lg*, the results are too scattered to reach any conclusion.

4.3 Path Effect

It has been argued that path effect is a rather important factor in spectral ratio studies (*e.g.* Frankel, 1989; Taylor, 1988). In order to access this effect, we have examined earthquakes from two different azimuths from WMQ to see if there is any detected difference in their spectral ratios characteristics. Earthquakes in Figure 1 are separated into two groups, west and east of WMQ. This separation is based upon the fact that the region west of WMQ may be more tectonically active than the region to the east of WMQ, which is more nearly a stable basin. The two groups of earthquakes are plotted in Figures 4a and 4b in two different symbols. There is a slight indication that the earthquakes to the west may be characterized by higher ratios than those to the east. This is inconclusive due to the high degree of scatter in the data.

Another approach is to determine whether signals propagating along the path from WMQ to E. Kazakh exhibit characteristics of large spectral ratios. We have identified two earthquakes that are within 20 degrees in azimuth from WMQ to E. Kazakh for which the signals travel along a similar path as do those from the explosions. These events are indicated as 89043b and 86348 in Figure 1. The *Pg*/*Lg* spectral ratios of these two events are computed and plotted in Figure 5 along with the rest of the results. These ratios fall among the earthquake population and are among the largest of all earthquakes, yet they are still distinctly separated from the explosion population. The results are not unexpected, as these two events are of uncertain depth (NEIS depth of 33km). As indicated in earlier analysis, deeper earthquakes are characterized by large spectral ratios. If these two events are indeed shallow events, the spectral ratios of these two events may serve as the upper bound for the earthquake populations. If on the other hand they are deeper earthquakes, this fact shall be easily discernible and it will not be necessary for such a discriminant to be applied, as this discriminant is designed for distinguishing shallow focus earthquakes from explosions.

5.0 CONCLUSIONS

A spectral ratio method can likely be used to discriminate between earthquakes and explosions in the Central Eurasia region, but the lack of ground truth information remains an obstacle. The narrow bandpass filtering scheme provides a full characterization of each seismic signal in the time and frequency domains. If the same event is observed at several stations, then we shall have some descriptions of the distance dependence of the wavetrain as well. The data characterizing the events will consist of descriptions of the absolute and relative amplitudes of the arrivals in various frequency bands and their time domain envelopes (including that of their codas as well). With the collected data, we shall also compile information that may be useful for providing physical explanations for the empirical results. Such information will include, but not be limited to, source depths, types of blasts, path characterization, and source mechanisms. Additional emphasis will be placed upon paths that may have anomalously efficient propagation of the regional phases.

6.0 ACKNOWLEDGMENT

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7.0 REFERENCE

Barley, B. J. (1979). On the use of seismometer arrays to locate sources of higher mode Rayleigh waves, *AWRE Report No. 054/78*, Atomic Weapons Research Establishment, Aldermaston, England.

Bennett, T. J., B. W. Barker, and J. R. Murphy (1988). Regional phases from East Kazakh seismic events, *Seism. Res. Letts.*, *59*, 151.

Campillo, M., J. Plantet, and M. Bouchon, (1985). Frequency dependent attenuation in the crust beneath central France from Lg waves: data analysis and numerical modeling, *Bull. Seism. Soc. Am.*, *75*, 1395-1411.

Evernden, J. F., C. B. Archambeau, and E. Cranswick, (1986). An evaluation of seismic decoupling and underground nuclear test monitoring using high-frequency seismic data, *Rev. Geophys.*, *24*, 143-215.

Frankel, A. (1989). Effects of source depth and crustal structure on the spectra of regional phases determined from synthetic seismograms, *DARPA/AFTAC Annual Research Review for FY89*, 97-118.

Goncz, J. H., W. C. Dean, Z. A. Der, A. C. Lees, K. L. McLaughlin, T. W. McElfresh and M. E. Marshall (1987). Propagation and excitation of *Lg*, *Sn*, and *P-Pn* waves from Eastern United States earthquakes by regression analysis of RSTN data, *TGAL-86-7*, Teledyne Geotech, Alexandria, Virginia.

Gupta, I. N. and J. A. Burnetti (1980), Amplitude-distance relationships for regional phases in shield regions, *SDAC-TR-80-7a*, Teledyne Geotech, Alexandria, Virginia.

Gupta, I. N., K. L. McLaughlin, and R. A. Wagner (1987). Attenuation of ground motion in the eastern North America, report for the Electric Power Research Institute, Teledyne Geotech, Alexandria, Virginia.

Hasegawa, H. S. (1985). Attenuation of Lg waves in the Canadian shield, *Bull. Seism. Soc. Am.*, *75*, 1569-1582.

Mechler, P., M. Nicolas, A. Chaouch, and B. Massinon (1980). Seismic crustal and subcrustal phases propagation, Final report, *Lavoratoire de Geophysique Appliquee*, Universite Pierre et Marie Curie, Paris, France.

Murphy, J. R., and T. J. Bennett (1982). A discrimination analysis of short-period regional seismic data recorded at Tonto Forest Observatory, *Bull. Seism. Soc. Am., 75*, 1077-1086.

Noponen, I. and J. Burnetti (1980). Alaskan regional data analysis. In "Studies of Seismic Wave Characteristics at Regional Distances", *AL-80-1*, Teledyne Geotech, Alexandria, Virginia.

Nuttli, O. W. (1973). Seismic wave attenuation and magnitude relations for eastern North America, *J. Geophys. Res.*, 78, 876-885.

Nuttli, O. W. (1980). The excitation and attenuation of seismic crustal phases in Iran, *Bull. Seism. Soc. Am., 70*, 469-485.

Nuttli, O. W. (1986a). *Lg* magnitudes of selected East Kazakhstan underground explosions, *Bull. Seism. Soc. Am., 76*, 1241-1252.

Nuttli, O. W. (1986b). Yield estimates of Nevada Test Site explosions obtained from seismic *Lg* waves, *J. Geophys. Res., 91*, 2137-2152.

Taylor, S. R., N. W. Sherman, and M. D. Denny (1988). Spectral discrimination between NTS explosions and western United States earthquakes at regional distances, *Bull. Seism. Soc. Am., 78*, 1563-1579.

Taylor, S. R., M. D. Denny, E. S. Vergino, and R. E. Glaser (1989). Regional discrimination between NTS explosions and western U.S. earthquakes, *Bull Seism. Soc. Am., 79*, 1142-1176.

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