ANALYSIS OF REGIONAL SEISMIC DATA FOR UNDERGROUND EXPLOSIONS

Won-Young Kim
Lamont-Doherty Earth Observatory of Columbia University

Mark Fisk and Steven Bottone
Mission Research Corporation

Sponsored by The Defense Threat Reduction Agency
Arms Control Technology Division
Nuclear Treaties Branch

Contract No. DSWA01-98-C-0152

ABSTRACT

In recent years, numerous regional seismic event discrimination studies have shown that the high-frequency (usually greater than 3–4 Hz), *P/S* spectral amplitude ratios of regional *P* (*Pg* or *Pn*) and *S* (*Sg*, *Sn* or *Lg*) waves observed at distance range from few kilometers up to about 2,000 kilometers, provide an efficient method to classify regional earthquakes, quarry blasts and underground nuclear explosions. The high-frequency *P/S* spectral ratios of vertical-component records, *P/S* spectral ratios of rotated, three-component regional records, as well as the *P/S* spectral ratio of the three-component regional records corrected for the free surface effect have been used depending upon the availability of data. The distance correction is also applied to *P/S* ratios which improves significantly the discrimination power of *P/S* ratios over uncorrected ratios, particularly if the events have data from wide distance ranges (*e.g.*, 3 to 17 degrees). Distance corrected and network averaged *P/S* spectral ratios provide transportability of the spectral ratio method to various regions worldwide. However, the *P/S* spectral ratio method is region dependent and we must find the best phases, frequency bands, and distance corrections for each region by using training data set with wide distance range, azimuthal coverage, and event size. There are many regions worldwide where there are lack of training data set. In this study, we focus on data collection and analysis of such regions – Novaya Zemlya, Russia and Semipalatinsk Test Site, Kazakstan, for evaluating the *P/S* ratios for regional seismic discrimination for CTBT monitoring.

We analyzed regional data from earthquakes, peaceful nuclear explosions, underground nuclear test around Novaya Zemlya, Russia to evaluate applicability of *P/S* ratio discriminant. In this region, data are available from the past underground nuclear explosions with magnitude $m_b(P)$ range from 4.5 to 6.5, while the useful earthquake data are limited to $m_b(P)$ 3.5 – 4.5. We report our analysis of the regional data to examine possible size (magnitude) dependence of regional high-frequency *P/S* spectral amplitude ratios as reported by Ringdal *et al*. (1999) for signals recorded at NORSAR from the Novaya Zemlya underground nuclear explosions. We also collected and analyzed regional data around Semipalatinsk Test Site, Kazakstan, where there are limited data available from few earthquakes. The regional data from the recent calibration explosions in Balapan and Degelen Mt. at various depth of burials are analyzed to shed light on whether the reported magnitude dependence of regional high-frequency *P/S* spectral amplitude ratios are due to yields of the explosions, or due to efficiency of *S* wave excitation from various burial depths of the sources.

OBJECTIVE

We seek practical methods of discrimination between different types of sources, in Novaya Zemlya, E. Kazakstan and W. China by using high-frequency *P/S* spectral amplitude ratios at regional distances. In particular we address the problems, for CTBT monitoring, posed by small, low-magnitude events, $m_b(P)$ smaller than 4.

RESEARCH ACCOMPLISHED

Recently, Ringdal *et al*. (1999) reported that *P/S* spectral amplitude ratios from 16 Novaya Zemlya

Key Words: CTBT monitoring; regional seismic discrimination; underground explosions

underground nuclear tests recorded at a low-gain vertical channel of NORSAR (Norwegian Seismic Array) appeared to be dependent upon the event size, and argued that comparing the *P/S* ratios of large underground nuclear tests (UNT) and small earthquakes could give rise misleading conclusions on event identification. The result of their study has some significance in applying the *P/S* ratios for classifying the explosions from earthquakes using the regional records in regions with few known small earthquakes and large UNTs in the past. For instance, Novaya Zemlya as well as Semipalatinsk Test Site in eastern Kazakstan regions had numerous UNTs ranging from magnitude $m_b(P)$ 4.5 to 6.5, while very few small earthquakes with magnitude range approximately $m_b(P)$ 3.5 to 4.5 have occurred around these test site regions. In particular, the *P/S* spectral ratios of the regional records from the Kara Sea event on August 17, 1997 have been analyzed by Richards & Kim (1997) using the data recorded at KEV (Kevo, Finland; Δ = 1040-1127 km, AZ=261-266°). Richards & Kim (1997) reported that the event is likely an earthquake based upon its location and the *P/S* ratios in the frequency band 3-8 Hz, and indicated that high-frequency *P/S* ratio is an efficient method to discriminate earthquakes and explosions around Novaya Zemlya test site.

In the following, we examine apparent magnitude dependence reported by Ringdal *et al*. (1999) in an effort to shed light on seismic event identification using the high-frequency *P/S* ratios of regional phases. We report further, on the *P/S* ratios of seismic records at regional distances from numbers of underground nuclear tests at Novaya Zemlya and Lop Nor Chinese test sites with different magnitudes.

Records from Novaya Zemlya Underground Nuclear Tests Recorded at NORSAR

We obtained waveform data recorded on a low-gain channel (NAO01) at NORSAR from 17 UNT from Novaya Zemlya used by Ringdal *et al*. (1999). The magnitude ranges of these UNT are from $m_b(P)$ 3.8 to 6.0 (see Table 1). The vertical records from selected events are plotted in Figure 1. Waveform data from the smallest event on Aug. 26, 1984 ($m_b(P)$=3.8) show extremely poor signal-to-noise ratio, in particular, there are no discernible *S* wave energy on the trace (Fig. 1), while the data from the event on Oct. 1, 1981 ($m_b(P)$ =5.97) have digitizing noise. Although the locations of the UNT's (Lilwall & Marshall, 1986; Marshall et al., 1994) are very close from each other (epicentral distance range of 2271 to 2287 km from NAO01 site), there are considerable variation on *S* wave amplitudes (group velocity between 4.5 and 3.5 km/sec) among the traces. The waveform data show that *S* wave amplitudes, starting from *Sn* arrival down to arrivals with group velocity 3.5 km/sec, are stronger on the traces from smaller events (e.g., Oct. 9, 1977 $m_b(P)$ =4.36 & May 7, 1988, $m_b(P)$=5.58),while *S* wave amplitudes are weaker relative to *P* waves on the traces from the large magnitude events (e.g., Aug. 10, 1978, $m_b(P)$ = 6.00). Since the source to station paths for these UNTs to NAO01 site are very similar, variations of these relative amplitude of *S* waves from UNTs might be due to the sources.

For Novaya Zemlya test site, the term underground nuclear explosions (UNEs) that we generally use should be distinguished from underground nuclear tests (UNTs), since each one of these "test" actually consisted of multiple UNEs carried out with some time delays in separate tunnels. When the time delays among the multiple explosions are long enough and when more than one explosions of a test have comparable yields, then these seismic events are known as "double" event (e.g., Oct. 18, 1979 and Oct. 11, 1980). Most of these tests may have complex shot patterns and depth of burials of each explosion. According to Mikhailov (1997), all of these underground nuclear tests consisted of multiple explosions in tunnels, except the two smallest tests on Oct. 9, 1977 and Aug. 26, 1984 which were listed as single explosion tests.

We analyzed waveform data from 15 UNTs at Novaya Zemlya test site. *Pn/Sn* spectral ratios are calculated for each discrete frequency band 1 through 5 Hz in order to examine the characteristics of the *Pn/Sn* ratios of these events. *Pn/Sn* ratios of these events in the frequency band 1 to 4 Hz are plotted in Figure 2. The regression of *Pn/Sn* ratios against magnitudes yield a slope of 0.14 with a standard deviation (σ) of 0.13 at 1 Hz, while the slopes and standard deviations at other frequencies are: 0.37 and σ =0.10 at 2 Hz, 0.23 and σ =0.13 at 3 Hz, and 0.04 and σ=0.11 at 4 Hz, respectively. Hence, the slope is the greatest at around 2 Hz, and suggests apparent magnitude dependence of the *Pn/Sn* ratios. However, the slopes are small at other frequencies and considering other factors such as depth of burials and complex shot patterns of these UNTs which might cause different efficiency of *S* wave excitation from each test, this may be considered "apparent" magnitude dependence of *Pn/Sn* ratio. Note also that these slopes of the regression are strongly affected by only two low magnitude events. In any case, relatively low *Pn/Sn* ratios at around 2 Hz from the two smaller UNTs may be caused by stronger *S* amplitudes relative to *P* wave at around 2 Hz from the single UNE.

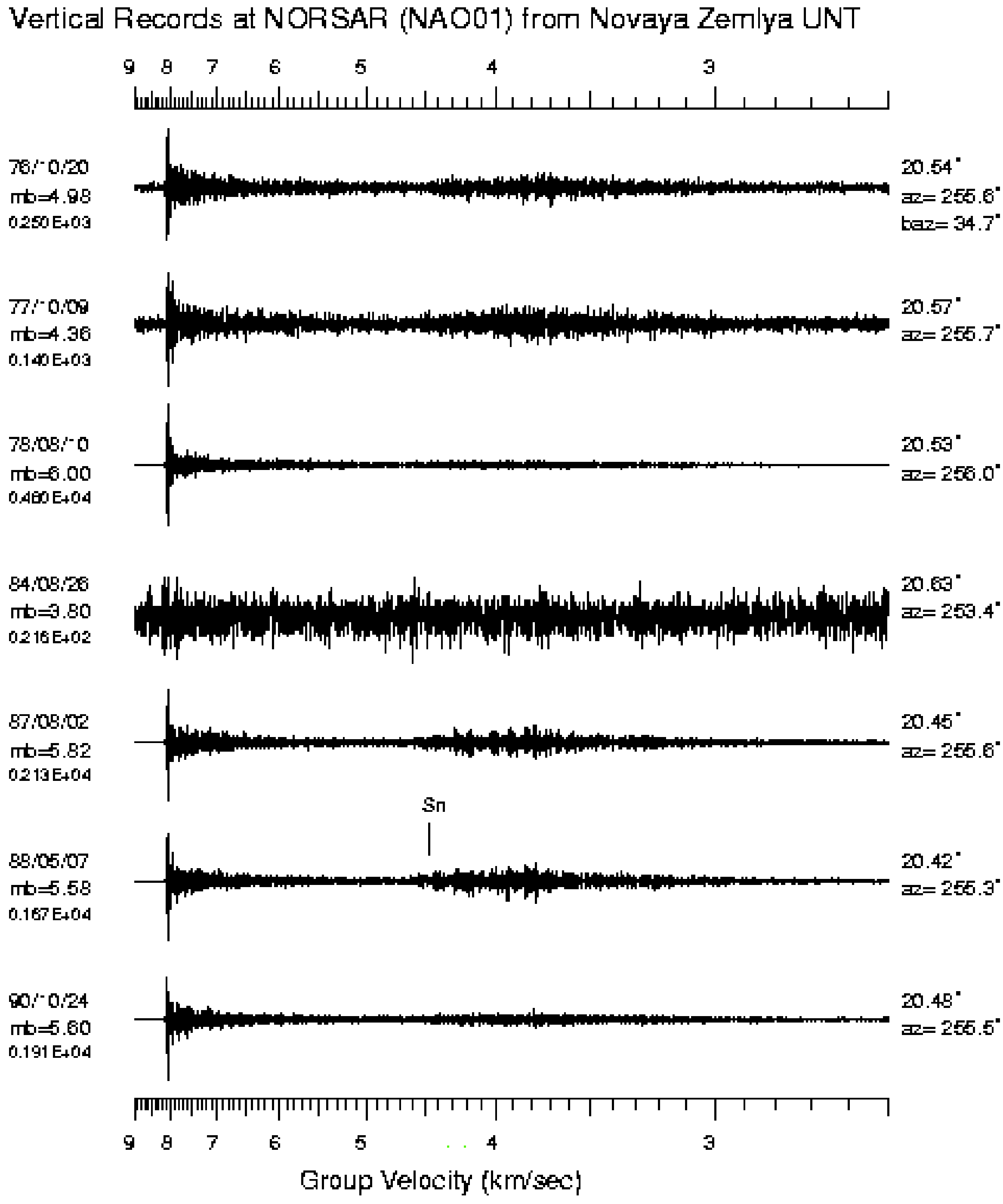

Fig.1 Selected waveform data from Novaya Zemlya underground nuclear tests recorded at a low-gain vertical channel (NAO01) at NORSAR. Events have magnitude, $m_b(P)$ 3.8 to 6.0 and epicentral distance ranges from 2271 to 2287 km with an average azimuth of 256°. Traces are plotted with group velocity in km/sec and the event id and magnitude for each event is indicated at the beginning of each trace.

Table 1. Novaya Zemlya Underground Nuclear Tests Recorded at NORSAR*

Origin time		Lat	Long	Magnitude		
Year-Mo-Da	(hh:mm:sec)	(°N)	(°E)	$m_b(P)$	N Obs.	Remarks
1976-Oct-20	07:59:58.07	73.398	54.821	4.98	39	
1977-Sep-01	02:59:57.97	73.339	54.628	5.66	84	
1977-Oct-09	10:59:58.12	73.409	54.936	4.36	28	
1978-Aug-10	07:59:57.93	73.291	54.892	6.00	91	
1979-Sep-24	03:29:58.75	73.343	54.681	5.77	104	
1979-Oct-18	07:09:58.75	73.316	54.825	5.79	91	double
1980-Oct-11	07:09:57.47	73.336	54.949	5.76	80	double
1981-Oct-01	12:14:57.23	73.304	54.827	5.97	100	bad data
1982-Oct-11	07:14:58.63	73.339	54.617	5.58	87	
1983-Aug-18	16:09:58.90	73.354	54.983	5.91	96	
1983-Sep-25	13:09:58.22	73.328	54.550	5.77	105	
1984-Aug-26	03:30:00.0	74.1	53.8	3.80	NAO	poor S/N
1984-Oct-25	06:29:58.12	73.355	54.999	5.82	104	
1987-Aug-02	02:00:00.20	73.326	54.611	5.82	99	
1988-May-07	22:49:58.34	73.314	54.562	5.58	92	
1988-Dec-04	05:19:53.30	73.366	55.010	5.89	94	
1990-Oct-24	14:57:58.45	73.331	54.766	5.60	0	

* Epicenter and magnitude from the report on Novaya Zemlya by Marshall et al. (1994).

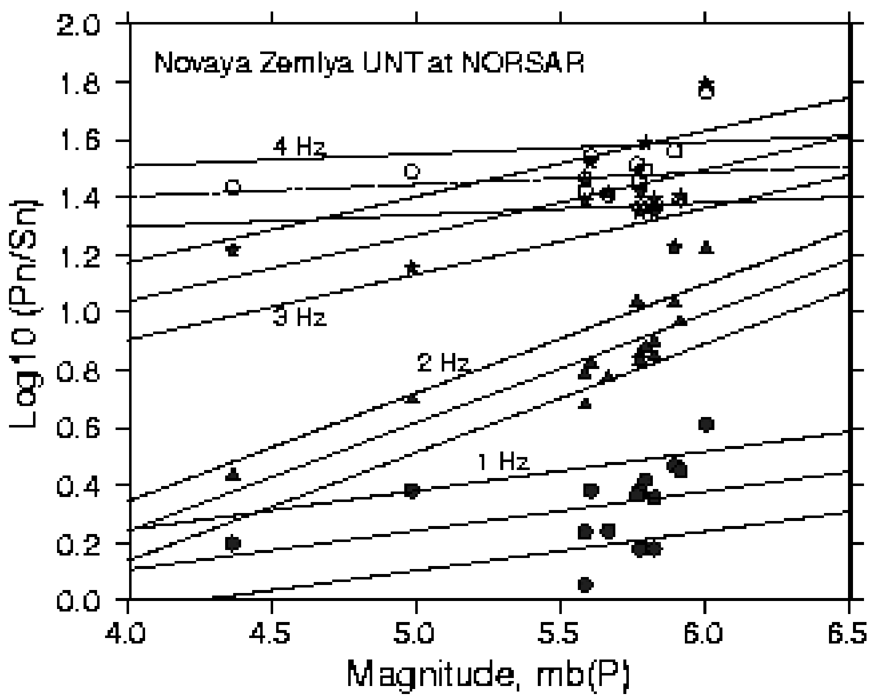

Fig. 2 Log_{10} (*Pn/Sn*) spectral ratios of each event are plotted against magnitudes for frequencies 1 to 4 Hz. The *Pn/Sn* ratios in the frequency bands 1–4 Hz indicates a weak magnitude dependence of *Pn/Sn* ratios. The slope (thick line) and the standard deviation (±2σ) of the regression (dotted lines) are plotted for reference.

Records from Lop Nor Underground Nuclear Tests at BRVK

We collected digital seismic records from 13 Chinese underground nuclear tests at Lop Nor recorded at BRVK (Borovoye) in northern Kazakstan. The data set include the first known underground nuclear test at Lop Nor on Sept. 22, 1969 and are the most records available at a single site at regional distances (see Table 2). Records from the UNT on Sept. 22, 1969 had only P waves, while records from three events had poor resolution. Hence, records from nine UNTs from Lop Nor at BRVK (Δ=1844–1895 km, AZ=319°) have been analyzed to examine if there is any indication of magnitude dependence of *P/S* spectral amplitude ratios among these events. The magnitude of these events ranges from $m_b(P)$ 4.9 to 6.2 and vertical component waveform data are shown in Figure 3. Records are plotted with group velocity in km/sec and magnitude is indicated at the beginning of each trace. BB indicate broadband signals from the new instrument (STS-2 sensors), while TSG-KS indicate signals recorded by STsR-TSG KS system (Kim & Ekström, 1996). The vertical records show clear *Sn* and *Lg* waves (Fig. 3), but note that *Sn* and *Lg* waves are less well excited by the smallest event on July 29, 1996 ($m_b(P)$=4.9), which is opposite to the case of records from Novaya Zemlya UNTs discussed in the previous section (Fig. 1).

The results of *Pn/Lg* spectral ratios are plotted against magnitude in Figure 4. The *Pn/Lg* ratios in the frequency bands 1-4 Hz indicates a very weak magnitude dependence of *P/S* ratios. The regression of Log_{10} (*Pn/Lg*) against magnitude yields a slope of 0.12 to 0.15 and a standard deviation of 0.07 to 0.10 in the frequency bands, 1–2 Hz and 3–4 Hz, respectively.

Table 2. Underground Nuclear Tests at Lop Nor Test Site Recorded at BRVK & MAK

Origin time		Lat	Long	Magnitude			
YearMoDa	(hh:mm:sec)	(°N)	(°E)	$m_b(P)$	M_S	Site	Remark
1969-09-22	16:14:58.8	41.386	88.296	5.2		H	P wave only
1976-10-17	05:00:03.7	41.649	88.161	4.9		H	poor resolution
1983-10-06	10:00:02.8	41.566	88.766	5.5	4.2	V	
1984-10-03	05:59:57.8	41.602	88.730	5.4		V	
1984-12-19	06:00:04.2	41.680	88.443	4.7	4.2		poor resolution
1987-06-05	04:59:58.3	41.584	88.737	6.2	4.7	V	poor resolution
1990-08-16	04:59:57.6	41.564	88.770	6.2	4.4	V	
1993-10-05	01:59:56.6	41.667	88.695	5.9	4.8		
1994-10-07	03:25:58.1	41.662	88.753	6.0			
1995-05-15	04:05:57.8	41.603	88.820	6.1	5.0		
1995-08-17	00:59:57.7	41.559	88.800	6.1			
1996-06-08	02:55:57.9	41.657	88.690	5.9	4.3		
1996-07-29	01:48:57.8	41.824	88.420	4.9			

Records from Lop Nor Underground Nuclear Tests Recorded at MAK

We analyzed digital seismic records from four latest Chinese underground nuclear tests at Lop Nor recorded at MAK (Makanchi) in northeastern Kazakstan. MAK is the nearest broadband seismographic station from Lop Nor outside of China. MAK is located about 755–796 km from the Lop Nor explosions with an azimuth of about 319° (Kim *et al*., 1996). The magnitude of these events ranges from $m_b(P)$ 4.9 to 6.1. The vertical component waveform data are shown in Figure 5. The event id, magnitude and zero-to-peak amplitude in micrometer/sec is indicated at the beginning of each trace. The vertical records from the four UNTs show considerable difference on *Lg* waves excitation (Fig. 5). *Lg* waves are well excited from the strongest UNT on May 15, 1996 ($m_b(P)$=6.1), while *Lg* waves are least excited by the smallest event on July 29, 1996 ($m_b(P\ )$=4.9). Although records from only four events are available, the excitation of shear wave energy from the Lop Nor UNTs are similar to the case of BRVK, but it is opposite to the case of records at NORSAR from Novaya Zemlya UNTs discussed in the previous section.

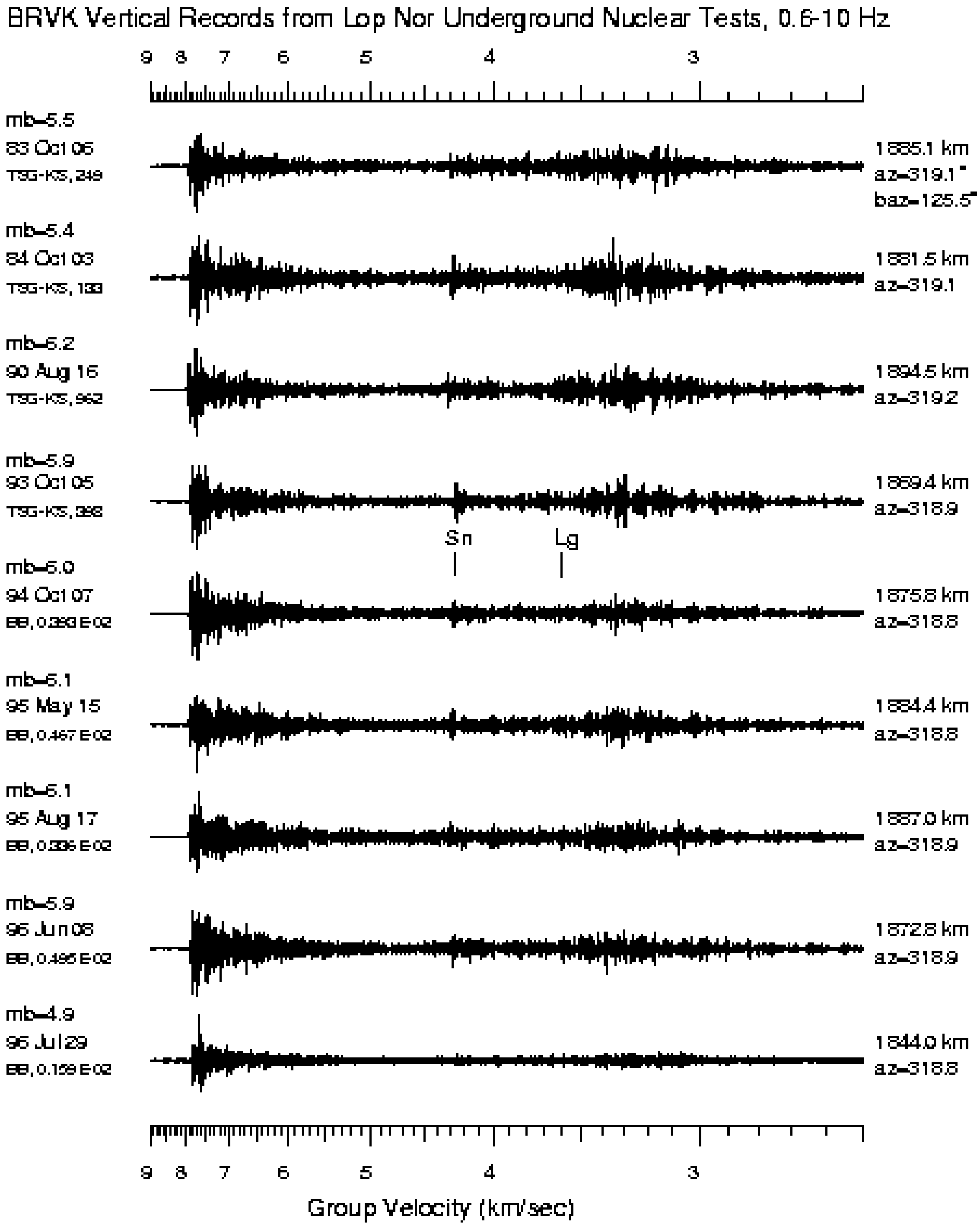

Fig. 3 Vertical component records at BRVK in northern Kazakstan from underground nuclear tests from Lop Nor. Records are plotted with group velocity in km/sec and magnitude, $m_b(P)$, of each event is indicated at the beginning of each trace. BB indicate broadband signals from the new instrument (STS-2 sensors), while TSG-KS indicate signals recorded by STsR-TSG KS system with SKM-3 sensor.

The Log_{10}(*Pn/Lg*) spectral ratios are plotted against magnitude in Figure 5. The *Pn/Lg* ratios in the frequency bands 1-7 Hz indicates no magnitude dependence of *P/S* ratios. Even the *P/S* ratios in the frequency bands 3-5 Hz indicates a negative slope against magnitude, which is due to the strong *P* wave spectral peak at this frequency band on signal from the event on July 29, 1996 (Figure 5). The results of this analysis suggest that the magnitude dependence of *P/S* ratios is not supported from this data set. Obviously, poor signal to noise ratios of *S* waves from weak UNTs at Novaya Zemlya recorded at NORSAR at far regional distances (Δ≈2280 km) might caused "apparent" magnitude dependence of *P/S* ratios.

CONCLUSIONS AND RECOMMENDATIONS

Pn/Sn spectral amplitude ratios of vertical-component records from 15 UNTs at Novaya Zemlya test site recorded at NORSAR (Δ = 2271–2287 km) show "apparent" magnitude dependence at certain frequency. *Pn/Sn* ratios of these events in the frequency band 1 to 4 Hz suggests that the magnitude dependence reported by Ringdal et al. (1999) is pronounced at around 2 Hz. This is may be due to a relatively low *Pn/Sn* ratios at around 2 Hz from the two smallest UNTs may be caused by stronger *S* amplitudes relative to *P* wave at around 2 Hz from the single UNE carried out for the two UNTs. Further, at frequencies 1, 3 and 4 Hz, size dependency of *Pn/Sn* ratios appear to be weak.

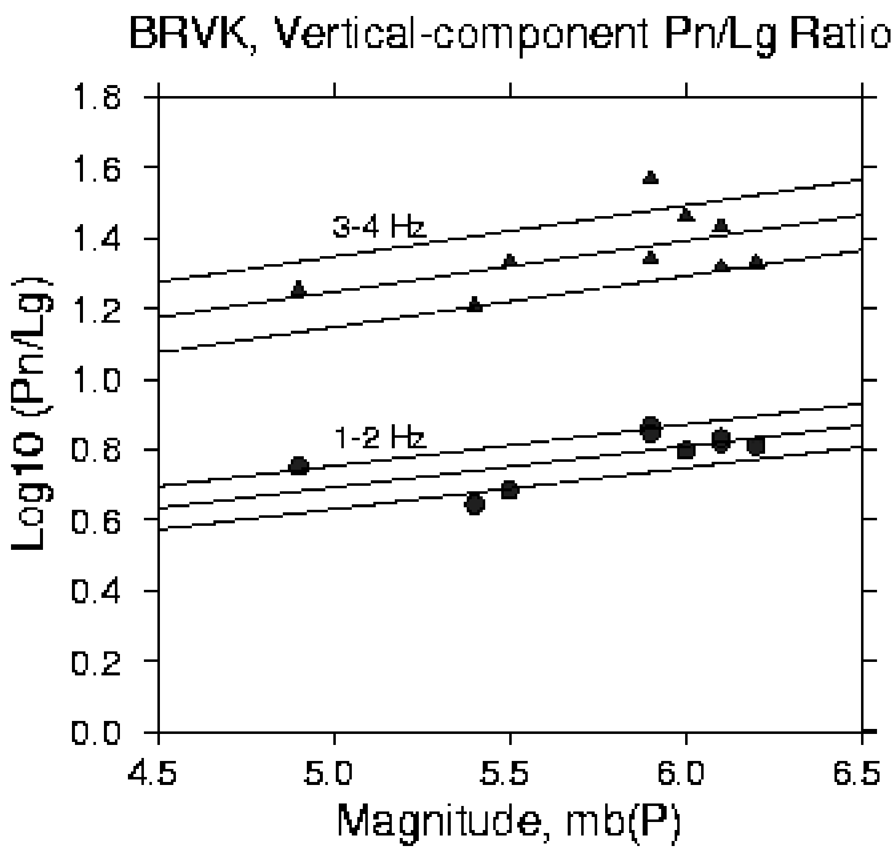

Fig. 4 Log_{10} (*Pn/Lg*) spectral ratios of each event are plotted against magnitudes for frequency band 1-2 Hz and 3-4 Hz. *Pn/Lg* ratios in the frequency bands 1-4 Hz indicate a very weak magnitude dependence of *Pn/Lg* ratios. The slope (thick line) and the standard deviation (±2σ) of the regression (dotted lines) are plotted.

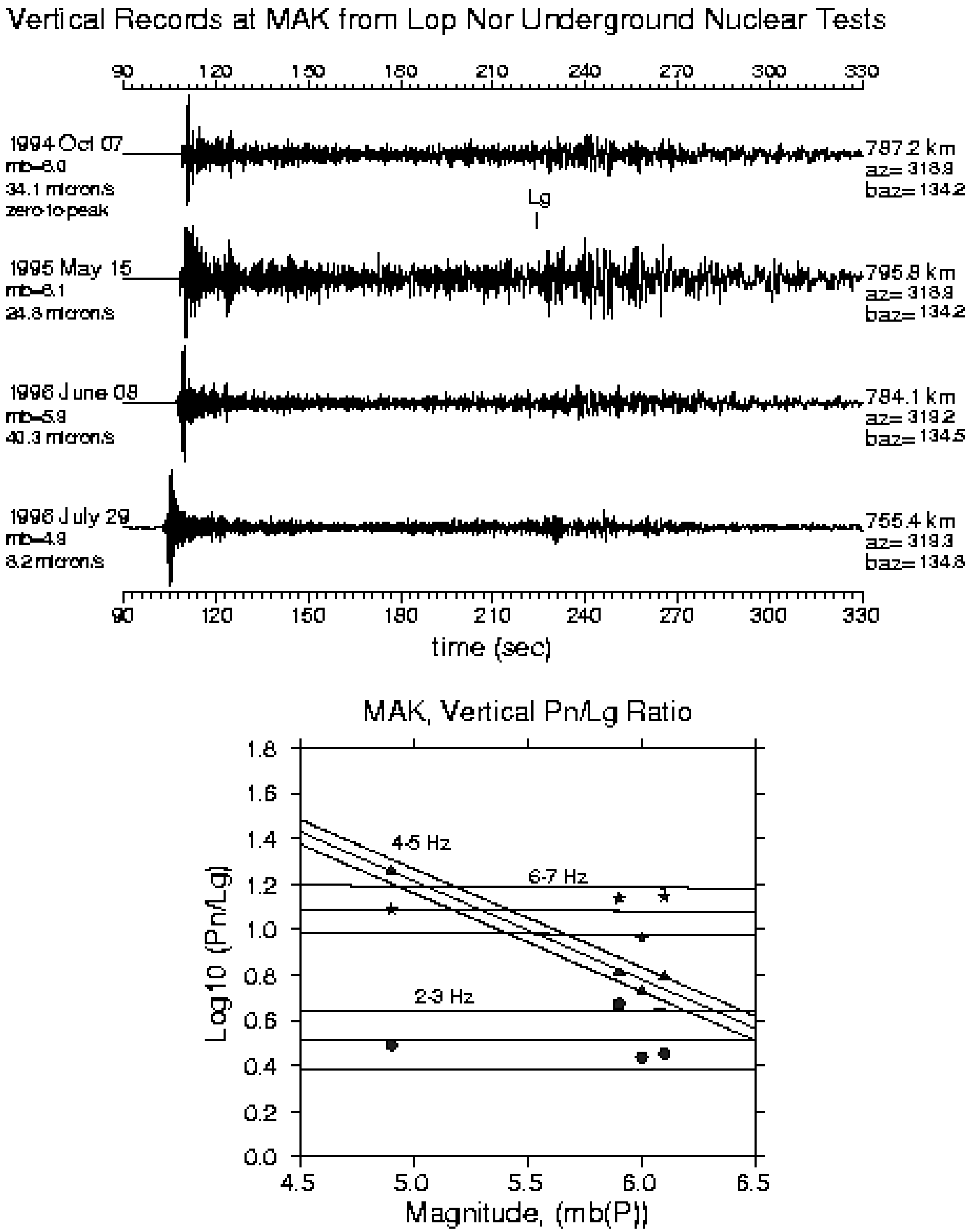

Fig. 5 (*upper panel*) Vertical records from four Chinese underground nuclear tests at Lop Nor recorded at MAK (Makanchi). Event id, magnitude and zero-to-peak amplitude in micrometer/sec is indicated at the beginning of each trace. Notice the considerable variation of *Lg* waves excitation from each event. (*lower panel*) $\mathrm{Log}_{10}(Pn/Lg)$ spectral ratios at three frequency bands are plotted against magnitude. Notice a negative slope at 4-5 Hz band, which is due to strong *P* wave spectral peak at this frequency on signal from the event on July 29, 1996.

Pn/Lg spectral amplitude ratios of vertical-component records from nine UNTs – magnitude ranges of $m_b(P)$ 4.9 to 6.2, at Lop Nor recorded at BRVK (Δ = 1844–1895 km, AZ = 319°) indicate that there is no clear magnitude dependence of *P/S* spectral amplitude ratios among these events (Fig. 4). We observed that *Sn* and *Lg* waves are less well excited by the smallest event on July 29, 1996 ($m_b(P)$=4.9), which is opposite to the case of records from Novaya Zemlya UNTs at NORSAR (Fig. 1).

Pn/Lg spectral amplitude ratios of vertical-component records from four Chinese underground nuclear tests at Lop Nor recorded at MAK (Makanchi) show no magnitude dependence of *P/S* ratios (Fig. 5). MAK is located about 755–796 km from the Lop Nor explosions with an azimuth of about 319°. The vertical records from the four UNTs show considerable difference on *Lg* waves excitation (Fig. 5). *Lg* waves are well excited from the strongest UNT on May 15, 1996 ($m_b(P)$=6.1), while *Lg* waves are least well excited by the smallest event on July 29, 1996 ($m_b(P)$=4.9). Although records from only four events are available for analysis, the excitation of shear wave energy from the Lop Nor UNTs at MAK are opposite to the case of records at NORSAR from Novaya Zemlya UNTs. The *Pn/Lg* ratios in the frequency bands 4–5 Hz even show a negative slope against magnitude, which is due to the strong *P* wave spectral peak at this frequency band on signal from the smallest event on July 29, 1996 (Figure 5).

The results of this study suggest that the magnitude dependence of *P/S* ratios is not supported by the regional data set we analyzed. Obviously, poor signal to noise ratios of *S* waves from weak UNTs at Novaya Zemlya recorded at NORSAR at far regional distances (Δ≈2280 km) , as well as spectral peaks in the source spectra at a particular frequency for low-magnitude events might have caused "apparent" magnitude dependence of *P/S* ratios.

High-frequency, three-component *P/S* spectral amplitude ratios of regional signals have been successfully applied to identify earthquakes signals from explosions (e.g., Kim *et al*. 1997). We recommend to use three-component *P/S* ratios whenever possible. We also collected waveform data from UNTs at Semipalatinsk test site and from PNEs (peaceful nuclear explosions) carried out by former Soviet Union for additional studies to examine further the magnitude dependence of *P/S* ratios as well as to improve discrimination between different types of sources using high-frequency *P/S* spectral amplitude ratios at regional distances. In particular we will address the problems posed by small, low-magnitude events for CTBT monitoring.

REFERENCES

Kim, W. Y., V. Aharonian, A. L. Lerner-Lam and P. G. Richards, Discrimination of earthquakes and explosions in southern Russia using regional high-frequency three-component data from the IRIS/JSP Caucasus Network, *Bulletin of the Seismological Society of America*, **87**, 569-588, 1997.

Kim, W. Y., V. Kazakov, A. Vanchugov and D. Simpson, Broadband and array observations at low noise sites in Kazakhstan: Opportunities for seismic monitoring of a Comprehensive Test Ban Treaty, in E. Husebye and A. M. Dainty (eds.), *Monitoring a Comprehensive Test Ban Treaty*, Kluwer Academic Publishers, 467–482, 1995.

Kim, W. Y. and G. Ekström, Instrument responses of digital seismographs at Borovoye, Kazakhstan by inversion of transient calibration pulses, *Bulletin of the Seismological Society of America*, **86**, 191–203, 1996.

Lilwall, R.C. and P. D. Marshall, Body wave magnitude and locations of Soviet underground explosions at the Novaya Zemlya test site, Atomic Weapons Research Establishment Report No. O17/86, HMSO, London, 1986.

Marshall, P.D., D. Porter, J.B. Young, and P.A. Peachell, Analysis of short-period seismograms from explosions at the Novaya Zemlya test site in Russia, Atomic Weapons Research Establishment Report No. O2/94, HMSO, London, 1994.

Mikhailov, V.N., *USSR Nuclear Tests: general characteristics, goals and organization of nuclear tests in the USSR*, edited by Mikhailov in Russian, Moscow, IZDAT, 1997.

Richards, Paul G. and Won-Young Kim, Testing the nuclear test-ban treaty, *Nature*, Vol. **389**, pp. 781–782, 23 October 1997.

Ringdal, F., Study of low-magnitude seismic events near the Novaya Zemlya nuclear test site, *Bull. Seism. Soc. Am.*, **87**, 1563-1575, 1997.

Ringdal, F., T. Kvørna, J. Schweitzer, E. Kremenetskaya and V. Asming, Research in Regional Seismic Monitorng, Proc. 21st Seismic Research Symposium: Technologies for Monitoring the Comprehensive Nuclear-Test-Ban Treaty, 21-24 Sept. 1999, Las Vegas, Nevada, 607-615, 1999.