SEISMIC CHARACTERIZATION OF NORTHEAST ASIA AND ANALYSIS OF THE NEVA PEACEFUL NUCLEAR EXPLOSIONS

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Sponsored by National Nuclear Security Administration
Office of Nonproliferation Research and Engineering
Office of Defense Nuclear Nonproliferation

Contract Nos. DE-FC52-2004NA25540[1] and W-7405-ENG-36[2]

ABSTRACT

Twelve peaceful nuclear explosions (PNEs) were detonated in the Yakutsk region of Russia in the 1970s and 1980s. In July and August 1987, three PNEs were detonated south of the village of Tas-Yuryakh in southwest Yakutia, in an attempt to increase oil production (Neva-2 and -3) and construct an underground oil storage facility (Neva-4) in the region. These explosions were recorded across the Yakutsk regional seismic network (event-station distances of between about 750 and 1400 km), but none of these data (origin parameters, arrival times and amplitudes) were ever published in either regional or international seismic bulletins. We present and interpret this previously unpublished Yakutsk data, including our new analysis of seismograms.

From analysis of the regional Neva PNE seismic data we find Pn and Pg velocities of 8.31 km/s and 6.16 km/s, respectively, and Sn and Sg velocities of 4.70 km/s and 3.59 km/s, respectively. These velocities are primarily valid for the eastern Siberian Platform, and are consistent with earlier studies.

Comparison between various Pg/Sg amplitude ratios of the Neva PNEs and those of regional earthquakes show that for a given distance or K-class (source size), the ratio is larger for explosions, and the best discriminants use only horizontal component Pg/Sg ratios. Neva-4 was detonated in salt, and plots closer to tectonic earthquakes than the Neva-2 and -3 PNEs, which may have implications for other discrimination scenarios. We also found that the Yakutsk network discrimination results, which were obtained using analog data, essentially match our previous results for the Neva explosion data recorded digitally at station HIA, China. Hence, the analog data from Yakutia can be used to demonstrate transportibility of discriminants to regions where no digital data from nuclear explosions exist.

Additional work we have undertaken over this past year include (1) compilation of a station book of northeastern Russia seismic stations including all obtainable station information and yearly instrument calibration curves; (2) a comprehensive analysis of all focal mechanisms that have been generated, reported, or published for continental eastern Russia with special emphasis placed on data source, data quality, and mechanism reliability; and (3) continued origin, arrival, and amplitude information to our Siberia seismicity database.

OBJECTIVES

The transportability of regional discriminants is an especially interesting topic as no new nuclear explosions have occurred in Asia for several years. We have analyzed previously unavailable seismic information from historic events to study crustal velocity models and to investigate regional discriminants in Yakutia. Our objective is to demonstrate that our previously estimated velocity models are valid and to demonstrate that analog amplitude data can be utilized to transport discriminants to a new region.

RESEARCH ACCOMPLISHED

Neva PNE Background Information

In July and August 1987, three PNEs were detonated south of the village of Tas-Yuryakh in southwest Yakutia, Russia, (Figures 1 and 2) in an attempt to increase oil production (Neva-2 and -3) and construct an underground oil storage facility (Neva-4) in the region (Fujita, 1995). These explosions were recorded across the Yakutsk regional seismic network, but none of the data were ever published in either international bulletins or Soviet regional seismic bulletins. However, the seismograms were analyzed and the data recorded in the Yakutsk network internal bulletin. Here we present and interpret previously unpublished Yakutsk data.

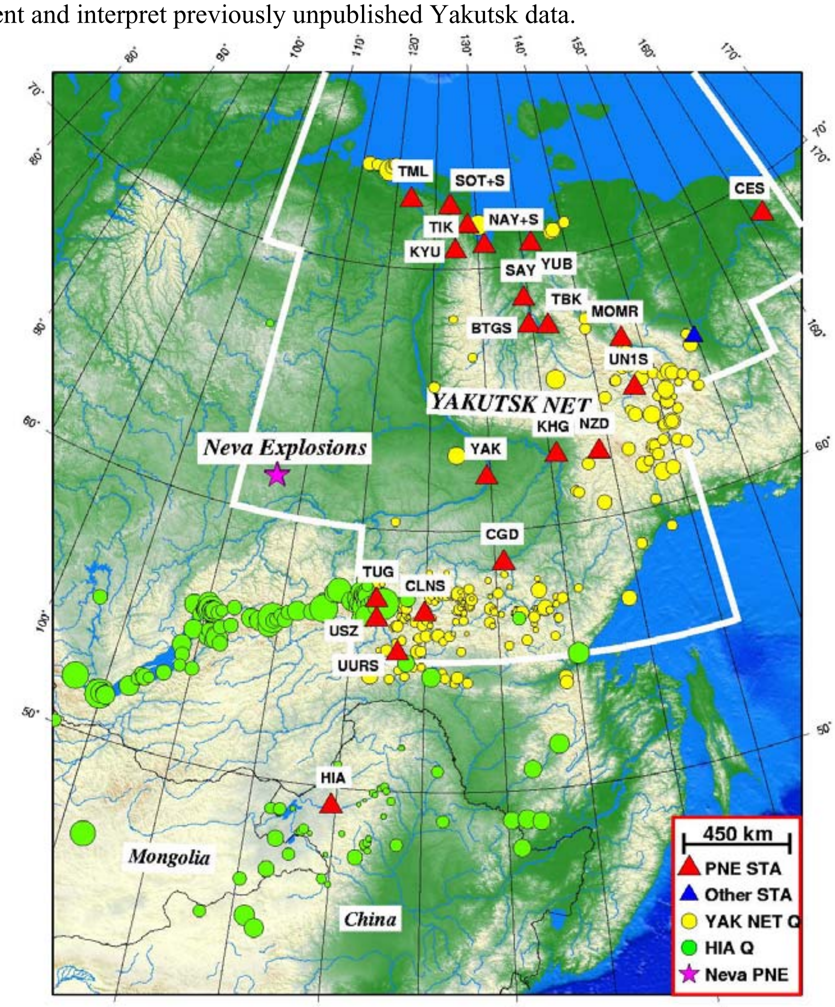


Figure 1. Yakutsk Network and station HIA in northeast China. We used arrival time and amplitude information from the Neva-2, -3, and -4 PNEs to conduct travel time and discrimination analysis for the stations shown in red. Yellow circles represent earthquakes recorded by the Yakutsk Network and green circles are earthquakes recorded digitally at HIA.

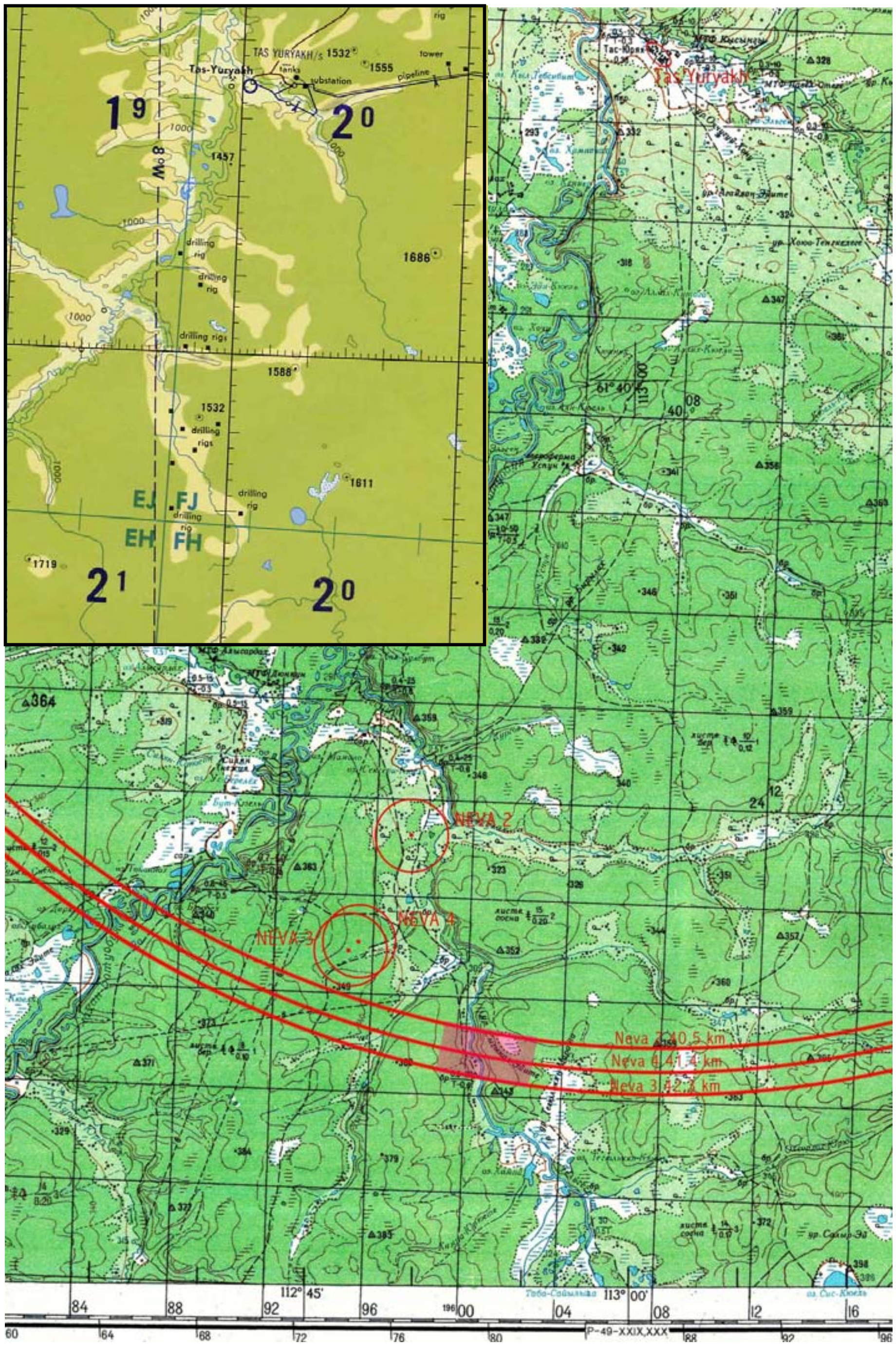


Figure 2. Tas'Yuryakh region showing the probable locations of the Neva PNEs. The inset covers the same geographic region as the main map and shows the locations of the oil fields associated with the Neva PNEs. The large map shows arcs representing the reported linear distances from the town to each PNE, with the shaded region the most likely area of detonation based on association with oil wells. Circled dots represent International Seismological Centre (ISC) seismically determined locations for the events. Grid line spacing represents approximately 4 km.

The general setting of the Neva -2, -3 and -4 PNEs, as well as a discussion of other PNEs in Yakutia and the Tas-Yuryakh region, can be found in Fujita (1995). Several locations have been reported for the Neva-2, -3 and -4 PNEs, including both instrumental and descriptive, though there seems to be no reported ground truth location.

Sultanov et al. (1999) report geodetically determined coordinates for many Soviet PNEs, but they report only seismic locations for the Neva explosions. Table 1 lists the various published locations of the events. Burtsev (1993) describes the events as having taken place south of Tas-Yuryakh in the basin of the Telgespit River. Specific parameters and locations being Neva-2 (13 kt in Borehole 68 at 1526.6-m depth in dolomite, 40.5 km south), Neva-3 (13 kt in Borehole 61 at 1515.2-m depth in dolomite, 42.3 km south), and Neva-4 (3.2 kt in Borehole 101 at 815.3-m depth in salt, 41.4 km south; Burtsev [1993], Mikhailova [1994]).

Table 1. PNE determinations

DATE	TIME	LAT.	LONG	DEPTH	MAG.	REF.
Neva-2						
19870706	23 59 46.00( )	60.3000	115.9000		5.6 mb	HFS
19870706	23 59 56.70( )	61.5010	112.8030	0.0	5.1 mb	NEIC
19870706	23 59 59.90( )	61.5000	113.2000	.		PEK
19870707	00 00 00.00( )	61.5000	112.4000	0.0	5.2 mb	NAO
19870707	00 00 00.00( )	61.5000	112.8500	1.502	5.1 mb	SUL*
19870706	23 59 56.93(0.2)	61.5014	112.8252	0.0	5.1 mb	ISC
Neva-3						
19870724	01 59 55.70( )	61.5000	112.7000		4.5 MS	PEK
19870724	01 59 56.80( )	61.4780	112.7530	0.0	5.1 mb	NEIC
19870724	02 00 00.00( )	61.5000	112.4000	0.0	5.2 mb	NAO
19870724	02 00 00.00( )	61.4500	112.8000	1.515	5.1 mb	SUL*
19870724	02 00 09.00( )	62.7000	112.7000		5.3 mb	HFS
19870724	01 59 56.93(0.2)	61.4574	112.7819	0.0	5.1 mb	ISC
Neva-4						
19870812	01 29 44.00( )	60.1000	116.4000		5.5 mb	HFS
19870812	01 29 55.90( )	61.5000	113.1000			PEK
19870812	01 29 56.80( )	61.4550	112.7600	0.0	5.0 mb	NEIC
19870812	01 30 00.00( )	61.5000	112.4000	0.0	4.9 mb	NAO
19870812	01 30 00.50( )	61.4500	112.8000	0.815	5.0 mb	SUL*
19870812	01 29 57.05(0.2)	61.4592	112.7887	0.0	5.0 mb	ISC

*Sultanov et al., 1999

We checked both instrumental and descriptive locations for consistency on U.S. air navigation charts (1:500,000 scale; tactical pilotage chart [TPC] D-7A; Figure 2 inset) and Soviet military topographic maps (1:200,000 scale; P-49-XXIII, XXVI;
Figure 2). Comparison of the ISC determined epicenters to the most likely location of the explosions based on cited distances and locations of oil drill rigs (see Figure 2) suggest the ISC locations are 8–10 km to the northeast. However, it is unclear if the distances given from Tas-Yuryakh are driving distances (road) or linear (as the crow flies). Given the historic difficulty in the use of accurate maps and/or coordinates in the Soviet Union, it would have been difficult to calculate an accurate linear distance. Overall, it is reasonable to consider that the distances from Tas-Yuryakh cited in Burtsev (1993) to be driving distances. Hence, the actual locations of the PNEs would be closer to Tas-Yuryakh and closer to the reported ISC epicenters. Overall, given the uncertainties involved in determining a ground truth location based on the location descriptions and available maps, the instrumental ISC determined epicenters appear to be sufficiently accurate to be useful in a basic seismic velocity study.

Travel Time Summary

We acquired seismograms from several Yakutsk network stations that recorded the 1987 Neva PNEs. Using the seismograms, we re-analyzed the arrival time picks for the southern Yakutsk stations, as well as northern stations. Our re-association of arrivals are depicted in Figure 3, along with travel-time curves that use ISC epicenter and origin time. Regressions calculated for Pg and Sg velocities assume an origin (0, 0) intercept.

By combining all new and corrected phase associations from the Neva-2, -3, and -4 PNEs and using the instrumentally determined ISC epicenter and origin time, we estimated best fitting velocities for P, Pg, S, and Sg phases (Figure 3). The velocities determined primarily reflect the seismic velocities of the eastern Siberian Platform, as all or most of each path is within it. The Pg (6.158 km/s) and Sg (3.594 km/s) velocities determined are consistent with the Pg and Sg velocities determined by a grid search method that obtained the best fitting crustal velocities for locating earthquakes (Figure 4; Mackey et al., 2003). In the study of Mackey et al. (2003), the Siberian Platform has elevated seismic velocities, averaging about 6.2 for Pg and 3.6 km/s for Sg, relative to other regions of eastern Russia. The similar elevated crustal velocities determined here from the Neva PNEs lend validation to the Mackey et al. (2003) model.

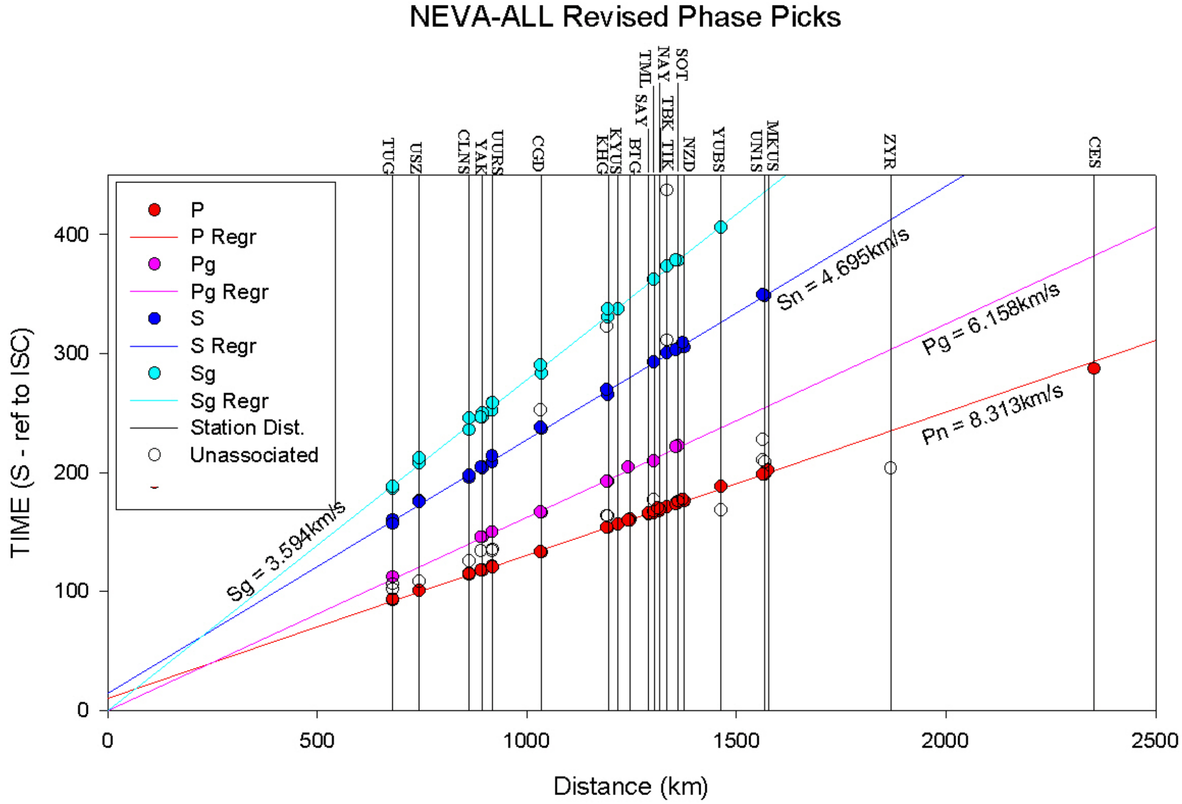


Figure 3. Travel time curves based on the NEVA PNEs.

Explosion Discrimination

Amplitudes from the Yakutsk network stations are available in the Yakutsk bulletin for the Neva PNEs, as are amplitudes for local and regional earthquakes. For the Neva-2 and -3 events, we reread amplitudes from available seismograms. We calculated amplitudes from our measurements following the standard operating procedures used in the Yakutsk network. Amplitudes are calculated by measuring the maximum peak to trough distance for a given phase. The measured amplitude is then divided by 2, and again divided by the station magnification in thousands. The resulting value is then reported as microns. Frequency of the arrival is not taken into account. Amplitudes for the Neva-4 PNE and some stations for Neva-2 and -3 were taken from the unpublished Yakutsk data bulletin.

To test discriminants, we also utilized amplitude data from several earthquakes that occurred across Yakutia in the 1980s and early 1990s (yellow circles, Figure 1). For earthquakes, we only selected amplitudes from stations that had also reported amplitudes for the PNEs. Unfortunately, because of analysis procedures used in the Yakutsk network, the Yakutsk bulletin does not list northern station amplitudes for southern region earthquakes, which restricts the available earthquake data at greater distances. PNE amplitudes are often three-component for P phases (Pn and Pg) and S (Sn and Sg) phases. Following the convention in our Russian data, we refer to Sg rather than Lg for the crustal S phase.

Using the available amplitudes, we formed various Pg/Sg ratios for the Neva PNE's and earthquakes. We tested vertical component discriminants (PgZ/SgH, Figure 5) and several other combinations of vertical and horizontal

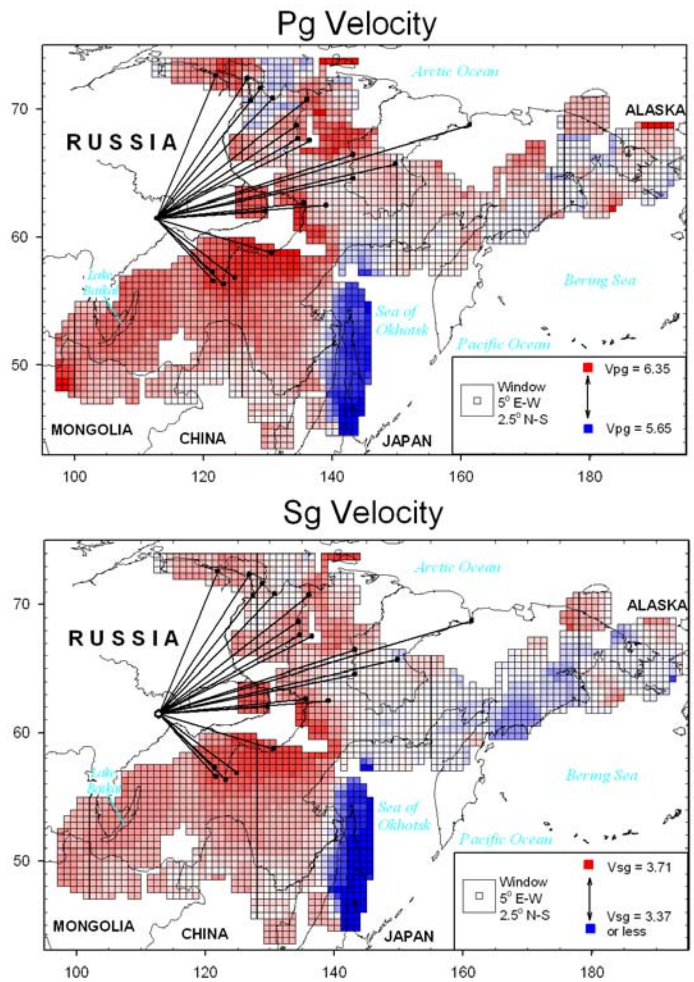


Figure 4. Velocity model of northeast Russia determined by Mackey et al. (2003). Elevated crustal velocities associated with the Siberian Platform determined in this model are consistent with velocities found in this study.

component ratios. Note that we show ratios from all stations, not just a single station in Figure 5. For each ratio type tested, we estimated a ratio-distance linear trend using only the earthquake data, and then removed that trend from both the earthquake and the explosion ratios. Figure 5A shows uncorrected ratios versus distances, and 5B shows the uncorrected ratios versus magnitude. Figures 5C and 5D show the corrected ratios versus distance and magnitude, respectively. In general, all combinations of amplitudes read from vertical and horizontal components form ratios that perform similarly to those in Figure 5A–C, though ratios using only horizontal amplitudes are slightly better.

Overall, regardless of components used, separation of the earthquake and explosion populations is quite good, especially considering that the amplitudes are measured from analog records without instrument corrections or band pass filtering, and the earthquakes are from such a broad geographic area. This separation is consistent with other Asian event discrimination studies (Hartse et al., 1997; Hartse, 2000). For comparison to discrimination performance of these same 3 PNEs using digital data, we show results from Hartse (2000) in Figure 5E and Figure 5F where he used HIA data and bandpass-filtered the waveforms prior to amplitude measurement. Clearly, the analog data have demonstrated that the regional Pg/Sg discriminant can be transported to northeastern Asia.

It is interesting to note that the amplitude ratios from Neva-4 are somewhat different. We find that the Pg/Sg ratios for Neva-4 plot roughly between the trends of ratios from the earthquakes and Neva-2 and -3 explosions (see Figures 5A and 5C). Neva-4 is also unusual in that the reported magnitudes are nearly identical (Neva-4 m_b 5.0 and Neva-2 and -3 m_b 5.1), even though Neva-4 was much smaller (3.2 kt) than Neva-2 and -3 (both 13 kt; see Table 1).

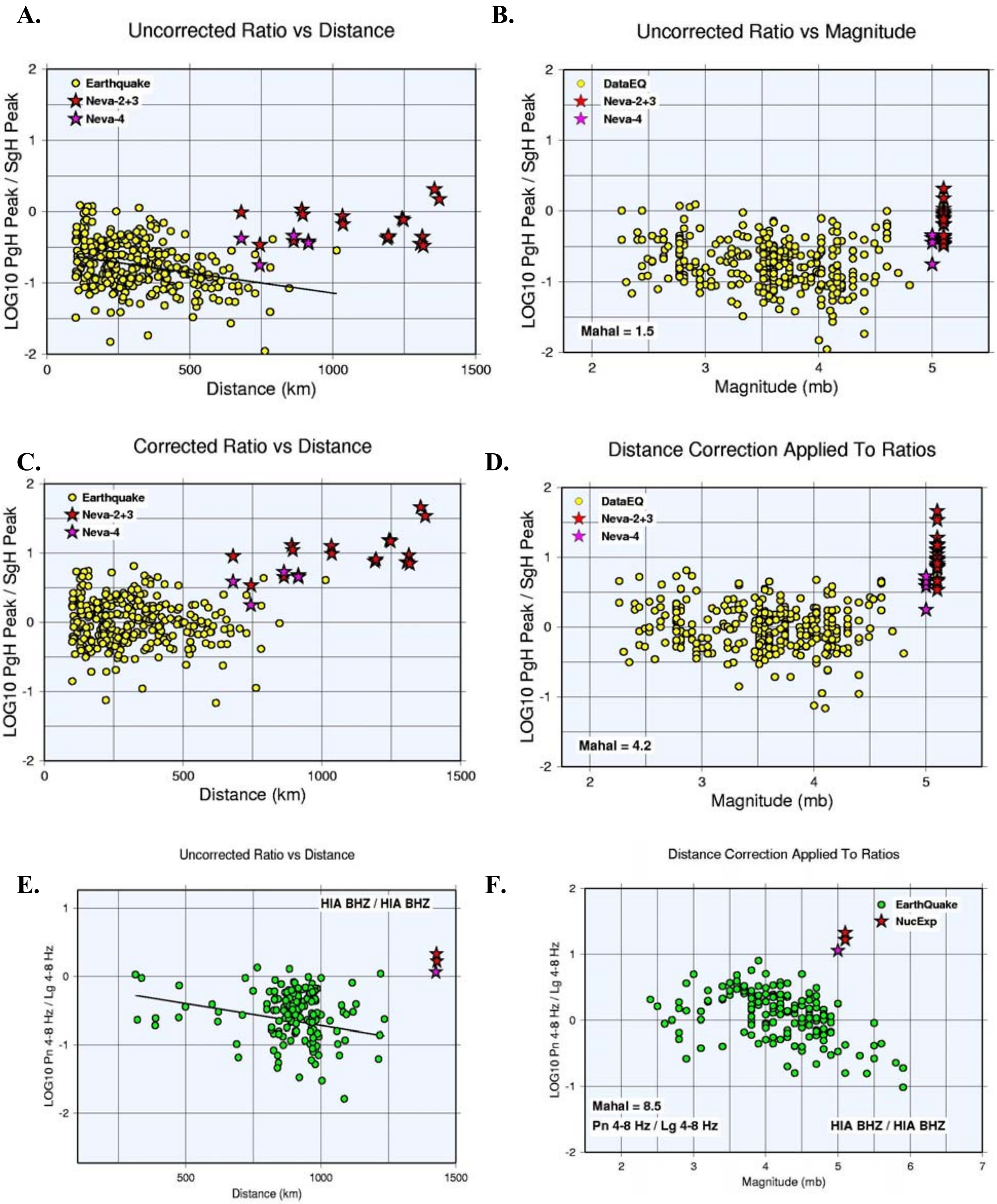


Figure 5. (A-D) Discrimination plots using PgH/SgH amplitude ratios of the Neva PNEs and tectonic earthquakes derived from analog stations in the Yakutsk network. Distance corrections are applied to C and D. (E, F). Discrimination plots between the Neva PNEs and earthquakes using digital data recorded at station Hialar (HIA) in China. The Hialar data were filtered to find the optimum frequency band for discrimination. A distance correction is applied to F.

Although the Neva-4 explosion was shallower (815.3 m) than Neva-2 (1526 m) and Neva-3 (1515.2 m; Fujita, 1995) all were overburied; thus, we do not believe that this is a result of depth of burial. The differences in Pg/Sg amplitude ratios and magnitudes between Neva-2 and -3 and Neva-4 may be explained by the type of rock in which the explosions took place. Neva-4 occurred in salt, while Neva-2 and -3 occurred in dolomite (Fujita, 1995). This suggests that seismic energy was better coupled for the nuclear explosion in salt, which may affect yield estimation. Also, nuclear explosions in salt may generate larger S-waves relative to P-waves when compared to other types of rock, thus plotted Pg/Sg amplitude ratios will appear closer to tectonic earthquakes than other nuclear explosions.

Despite the fact that this brief discrimination study is based on analog data, it is important that we observe separation between nuclear explosion and earthquake populations based on P/S amplitudes for the eastern Siberian Platform because little regional nuclear explosion data are available from the area. This study also confirms that it is possible to conduct discrimination studies using historic Soviet regional station data. Specifically, all of the Yakutsk network stations used here operated either SKM, VEGIK, or SM-3 short period seismometers recorded on photopaper.

Other Research

We have begun compilation of two major data sets, the first being a complete inventory of seismic stations that have operated in eastern Russia, and the second being a compilation of all focal mechanisms that have been determined for the study area. Both data sets are being compiled in a loose leaf format so that additions and corrections can easily be made without the need to reprint the entire document. Both documents are based on published Russian and western literature, discussions with Russian seismologists, and our own personal observations or studies.

Station Book

The seismic station inventory consists of one or more pages per station and includes information on station codes (formal and informal), site information (including maps), station history, instrumentation, response curves for the instruments, and other known information about the station, such as noise levels, type of recording, etc. A sample page is presented in Figure 6.

OCH – Omchak

Station: OCH - Omchak

Network: Magadan

Alternate Codes: English - OCHR
Russian - ОМЧ

Open Date: 01 October 1999
Close Date: Open

Location:				
	61.665N	147.867E	820m	Starovoit and Mishatkin, 2001
	61° 39' 55.0"N	147° 52' 00.0"E	820m	Starovoit and Mishatkin, 2001

Instruments:

MSU PAR4CH digital station (01-10-1999 – Present)

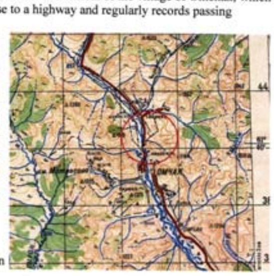
Instrument	Component	A/D Resolution	Sample Rate	Frequency Range (Hz)	v m/s/count a m/s^2/count
SM-3	N-S, E-W, Z	24 bit	50	0.2 - 1	2.80E-8

Recording History: Station Omchak was opened in September 1999 using equipment from the closed Nelkoba station. The station originally opened using an 8 channel 24 bit A/D and a Magadan designed and constructed amplifier. This amplifier caused significant noise problems with the station. The recording system was replaced in 2003 with a 4 channel 24 bit A/D converter with an internal amplifier. Timing is GPS.

Vault Foundation: The vault is located approximately 10m inside a shale bedrock tunnel. The tunnel was originally constructed to be a cold storage facility.

Site Description: Station Omchak is located a couple kilometers north of the village of Omchak, which is near the Martosoba gold mine. The station is close to a highway and regularly records passing vehicles.

Station Omchak Tunnel



Station Omchak location

Figure 6. Sample page from the Station inventory.

Coordinates, and locations on maps, have been taken from the best possible information, including site visits. Response curve information is taken primarily from those published in Russian operational bulletins (e.g., the instrument supplement to *Materialy po Seismichnost' Sibiri*). Photographs of the station are provided when available, and were primarily taken by the senior author. Station history information has been compiled not only from the published literature but in discussions with station operators. In many cases, stations have been moved over their lifetime even though the same station code (and even station coordinates!) has been maintained. Station locations are shown on Soviet military topographic maps of 1:200,000 scale (U.S. TPCs and maps at other scales have been used when necessary or available). Information detail varies somewhat by station; for the exact locations of some temporary stations are poorly known. So far we have completed the inventory for the Magadan and Yakutsk seismic networks. This inventory will continue to be updated and expanded in the future.

Focal Mechanism Compilation

We have also started compiling a listing and analysis of focal mechanisms which have been determined for continental eastern Russia (see Figure 7). To date, the compilation has been completed for the Stanovoi, Amur, and Chersky seismic regions. These compilations include all known focal mechanisms reported in the published Russian and western literature, along with unpublished mechanisms determined by the Michigan State group over the past 20 years. Focal mechanisms are given as strike, dip, and rake for both nodal planes. The source and the method (data sources) used are tabulated. Where available, a figure showing the data used is included when mechanisms have been determined using P-wave first motions, Rayleigh wave radiation patterns, or synthetic seismograms. For many Russian computer grid-search determined mechanisms, no figure is available. Based on these data, the mechanisms have been qualified as "Poorly Constrained" or "Unknown" (no data available to judge). Mechanisms that appear reasonably well constrained are not qualified and interpretation is left to the user. A "preferred solution" has been selected (which need not be well constrained) when multiple solutions are available. Typographical errors in various publications, errors arising from reversed sign conventions and projections, and other inconsistencies are noted where they have been identified. Additional comments are included which note other citations of the solution, problems in the original or secondary sources, major inconsistencies, and problems with orthogonality of the nodal planes.

June 5, 1978

1978 June 5 : 07 05 59. UTC

Latitude	Longitude	Depth	Mo (N-m)	K	m_b	M_S	M_w	Sources
60.13	160.41		2.05×10^{16}					HRV

α_1	δ_1	λ_1	α_2	δ_2	λ_2	Source	Notes	Method	Quality
6	26	119	165	67	77	Harvard		CMT	Figure 1 Preferred solution
306	48	90	126	42	90	McMullen (1985)	Poorly constrained	P-waves	Figure 2
303	50	95	115	40	83	McMullen (1985)	As cited by Imaev et al. (1990)	P-waves	Figure 2

COMMENTS

- The CMT solution is consistent with the first motion data except for YAK.
- The CMT solution is also cited by Riegel (1994).
- The McMullen (1985) solution is also cited in Imaev et al. (1990) and Fujita et al. (1990a).

Fig. 1

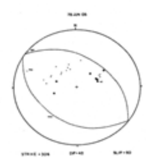


Fig. 2

Figure 7. Sample page from focal mechanism compilation.

CONCLUSIONS AND RECOMMENDATIONS

Separation between nuclear explosion and earthquake populations based on P/S amplitudes are observed in analog data from the Neva explosion sequence in the southeastern Siberian Platform. Our work also confirms that it is possible to conduct discrimination studies using historic Soviet regional station data. The next step is to determine whether similar discriminants are applicable to industrial and chemical explosions which occur in mining districts in eastern Russia. A large quantity of amplitude information is available in the MSU database; however, considerable filtering of the data set will be required before analyzing the smaller industrial explosions.

Enhanced quality control of the Michigan State University data set and improvement of station parameters continue and production of a usable, adaptable, station book is underway. This information will assist in identifying problem or abnormal stations as well as improving travel times and velocity models. We are also working on a focal mechanism compilation for eastern Russia, which will provide baseline information on regional tectonics and the ambient stress regime.

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