ANALYSIS OF DIGITIZED SEISMOGRAMS FROM RUSSIAN GEOPHYSICAL SURVEY STATIONS OF SOVIET PEACEFUL NUCLEAR EXPLOSIONS

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ABSTRACT

Throughout the 1970s and 1980s, the permanent seismic stations of the Soviet Union recorded over 100 peaceful nuclear explosions (PNEs) detonated within the Soviet Union. These records represent a large data set that has not been fully utilized. Digitization and analysis of the historic seismograms has allowed the extension of long-range PNE profile data into geographic regions not previously covered. Although the resolution of the profiles is limited by the distribution of permanent seismic stations operating at the time, the first long range profiles have been constructed through the Magadan and Chukotka regions. The Magadan region profile indicates velocities slower than those found from Kimberlite-4, the closest of the old PNE profiles. Western portions of the Magadan profile associated with the Siberian Platform and western Verkhoyansk Fold Belt are elevated relative to iasp91. Beyond the platform in the tectonically active areas, velocities are reduced and closer to iasp91. The Chukotka profile shows elevated velocities relative to iasp91, which decreases at station Zyryanka on the Kolyma-Omolon Superterrane. The delayed P arrival may be an effect of the large Indigirka-Zyryanka Basin in the vicinity of the station. Continuing east through Chukotka, velocities are much closer to iasp91. The digitized historic seismograms will be useful for explosion discrimination and other studies if the data are reliable and of sufficient quality. A direct comparison relating digitized short-period photopaper records to modern digital data was conducted to establish the range of useful frequency content and quality of data. For this study, digitized short period (Russian SKM seismometer) photopaper seismograms recorded at Yuzhno Sakhalinsk from September 2008 were compared to seismograms from the IRIS GSN station at Yuzhno Sakhalinsk (YSS). Seismograms show nearly identical waveforms and amplitude content in the 1-5 Hz range for all three components. Below 1 Hz, the amplitude response of the digitized records drops-off due to different instrument responses, but is probably correctable down to about 0.3 Hz. From 5-8 Hz, the general amplitude response is similar, though specific frequency spikes do not correlate well and there is deterioration in the correlation of waveforms. The digitized PNE data will result in useful seismic discriminants that utilize frequencies in the 1-5 Hz range for many different regions of Eurasia.

OBJECTIVES

This study seeks to obtain, scan, digitize, and analyze seismograms from Soviet permanent seismic station networks of Soviet PNEs. The analysis seeks to better resolve the crustal and velocity structure of Russia, particularly the Russian Far East where Deep Seismic Sounding (DSS) profiles using the PNEs were not conducted.

RESEARCH ACCOMPLISHED

Seismogram Acquisition and Digitization

We are working with the Institute for Petroleum Geology and Geophysics (IPGG) in Novosibirsk and several other institutes and seismic networks to assemble, digitize, and analyze PNE seismograms from seismic stations of the regional networks of Russia. Figure 1 shows the raypaths of seismograms already collected and scanned or digitized in this study. The original photopaper records are scanned at high resolution (usually 600 dpi) to preserve faint traces. The digitization process is manual, with as many points along the trace entered as needed to create an un-aliased waveform (Figure 2). The digitized seismogram is then re-sampled at 20 or 50 sps, depending on the frequency content of the seismic signal, regional trends in the data are removed, time corrections are applied, and amplitudes are converted to microns.

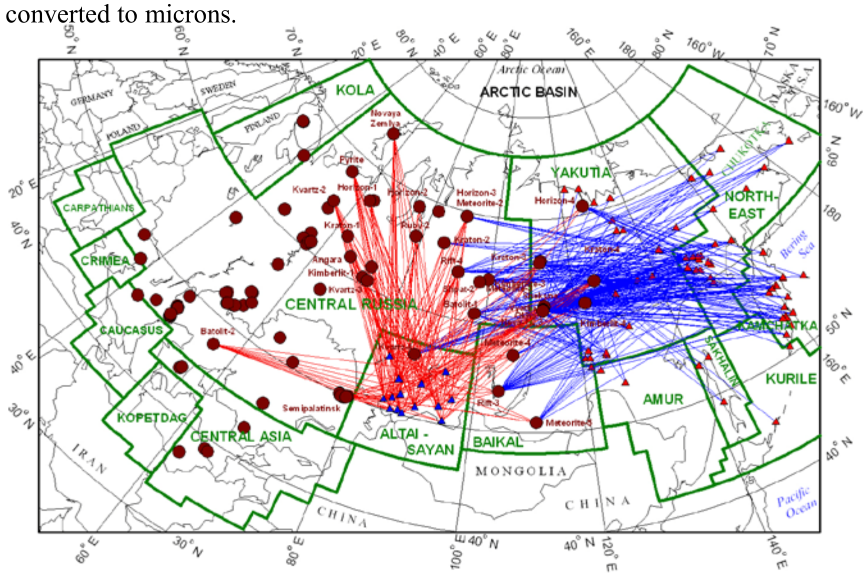

Figure 1. Raypath coverage of PNE seismograms acquired, scanned, and/or digitized for this study. Large dots indicate PNE locations and triangles indicate seismic stations. Blue paths indicate MSU holdings and red are IPGG holdings.

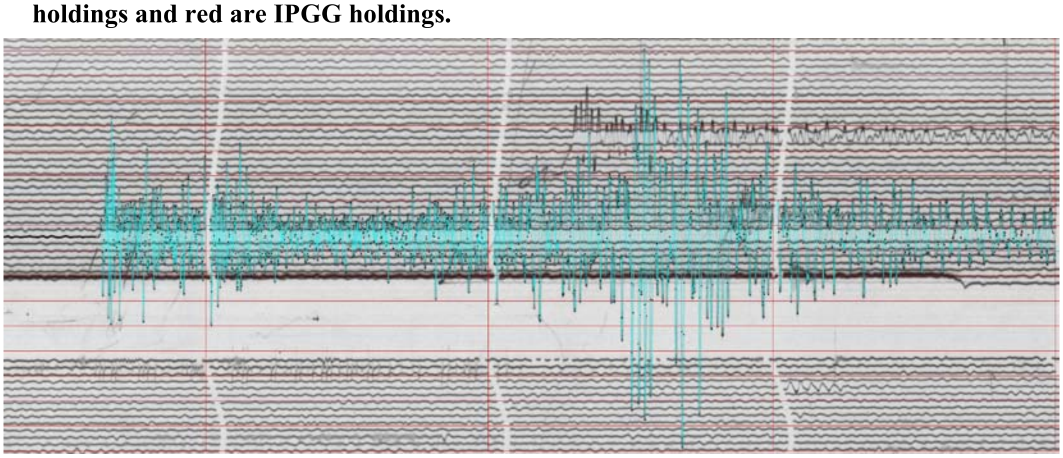

Figure 2. Sample record of the digitization process showing the vertical component of the Neva 2-2 PNE as recorded at Ust'Nyukzha (746 km distant).

Quality of Digitized Seismograms

To verify the quality of data from the digitized photo paper records, it is necessary to make a direct comparison with modern digital data. Many of the seismograms collected here are from sites currently operating as IRIS GSN digital stations, though conduction of the PNEs ceased prior to the opening of these Russian digital stations. Fortunately, as a part of their tsunami warning system, Yuzhno Sakhalinsk continues to operate an older style photo paper station co-located and in parallel with the IRIS GSN station at Yuzhno Sakhalinsk (YSS). The tsunami warning station is 3-component and records short period (0.3-0.83 second dominant period) SM-3 seismometers. Recording is on photo paper at 60 mm/min with an amplification of 22,230, and appears to use the older radio-clock timing system. In virtually all aspects, the YSS tsunami warning station and its seismograms are identical to those being digitized in this study.

Several Yuzhno Sakhalinsk tsunami warning station photo paper seismograms containing a variety of event sizes and hypocentral distances from September 2008 were acquired. The seismograms were scanned at 600 dpi and digitized in the same manner as the PNE records in this study. To preserve a truly independent analysis and quality test of the digitized waveforms, digital data from the co-located IRIS GSN station (YSS) was not viewed or referenced in any way during the selection or digitization of the photo paper records.

The waveforms, amplitudes, and frequency content of events digitized from the photo paper records and those recorded at the IRIS GSN station were compared. Generally, seismograms show nearly identical waveforms and amplitude content in the 1-5 Hz range for all three components. Below 1 Hz, the amplitude response of the digitized records drops-off due to different instrument responses, but is probably correctable down to about 0.3 Hz. From 5-8 Hz, the general amplitude response is similar, though specific frequency spikes do not correlate well and there is deterioration in the correlation of waveforms. The frequency responses and waveform correlation vary slightly from event to event.

Two specific test examples are shown. The first, depicted in Figure 3, is a small local event about 20 km from station YSS. Figure 3a plots the raw 3 component digitized data derived from the photo paper record. Figures 3b–d, left, compare the frequency-amplitude content of the GSN and digitized photo paper data of both the complete event waveform and a representative section of background noise. The Z and E-W components match very well in the 1–5-Hz range having nearly the same amplitudes and peaks in the response. From 5–7 Hz, the amplitude responses of the GSN data are higher on the Z component, and lower on the E-W component, but with peaks at the same frequencies. The N-S component responses match similar amplitudes from low frequencies through about 7 Hz, though there are discrepancies in the peak locations above 2 Hz. Figures 3b-d, right, depict waveform overlays by component of the GSN and digitized photo paper data bandpass filtered 1–5 Hz. For all three components, comparison of the overlaid components reveals several things. The overall character of the waveform is nearly identical. Virtually all the waveform peaks from the hand digitized data match those of the GSN data in terms of time, frequency, and shape. Inflections in both seismic traces also match quite well. One discrepancy that we note is a lower amplitude first motion on the GSN trace compared to the hand digitized data.

The second test example, shown in Figure 4, is a larger, deep event several hundred kilometers distant. Figure 4a plots the raw 3 component digitized data derived from the photo paper record. Figures 4b-d, left, compare the frequency-amplitude content of the GSN and digitized photo paper data of both the complete event waveform and a representative section of background noise. All components match very well in the 0.9–5-Hz range with nearly identical shapes in the response curve. From about 0.3–0.9 Hz, the response curves show the same peaks, but diverge with lower frequency. At frequencies above 5 Hz, the overall response is similar though individual peaks generally do not correlate. Figures 4b-d, right, depict waveform overlays by component of the GSN and digitized photo paper data bandpass filtered 1–5 Hz. As in Figure 3 above, the overall character of the waveform is nearly identical. Virtually all the waveform peaks from the hand digitized data match those of the GSN data in terms of time, frequency, and shape. Inflections in both seismic traces also match quite well.

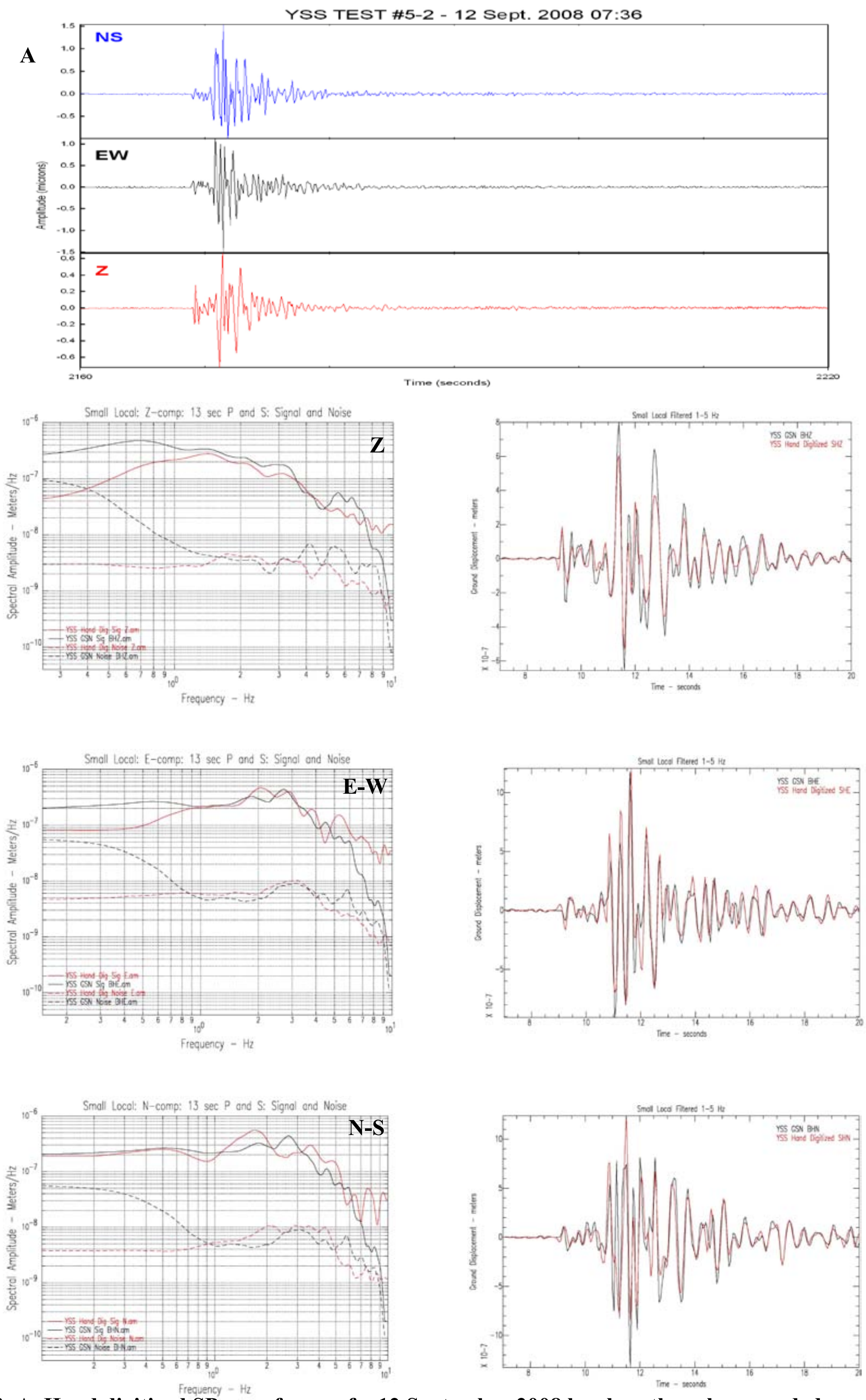

Figure 3. A. Hand digitized SP waveforms of a 12 September 2008 local earthquake recorded on photo paper at Yuzhno Sakhalinsk. B-D. Comparisons of frequency responses (left) and waveforms (right) of the digitized data to GSN data from the co-located IRIS station (YSS). Components are, top to bottom, Z, E-W, and N-S.

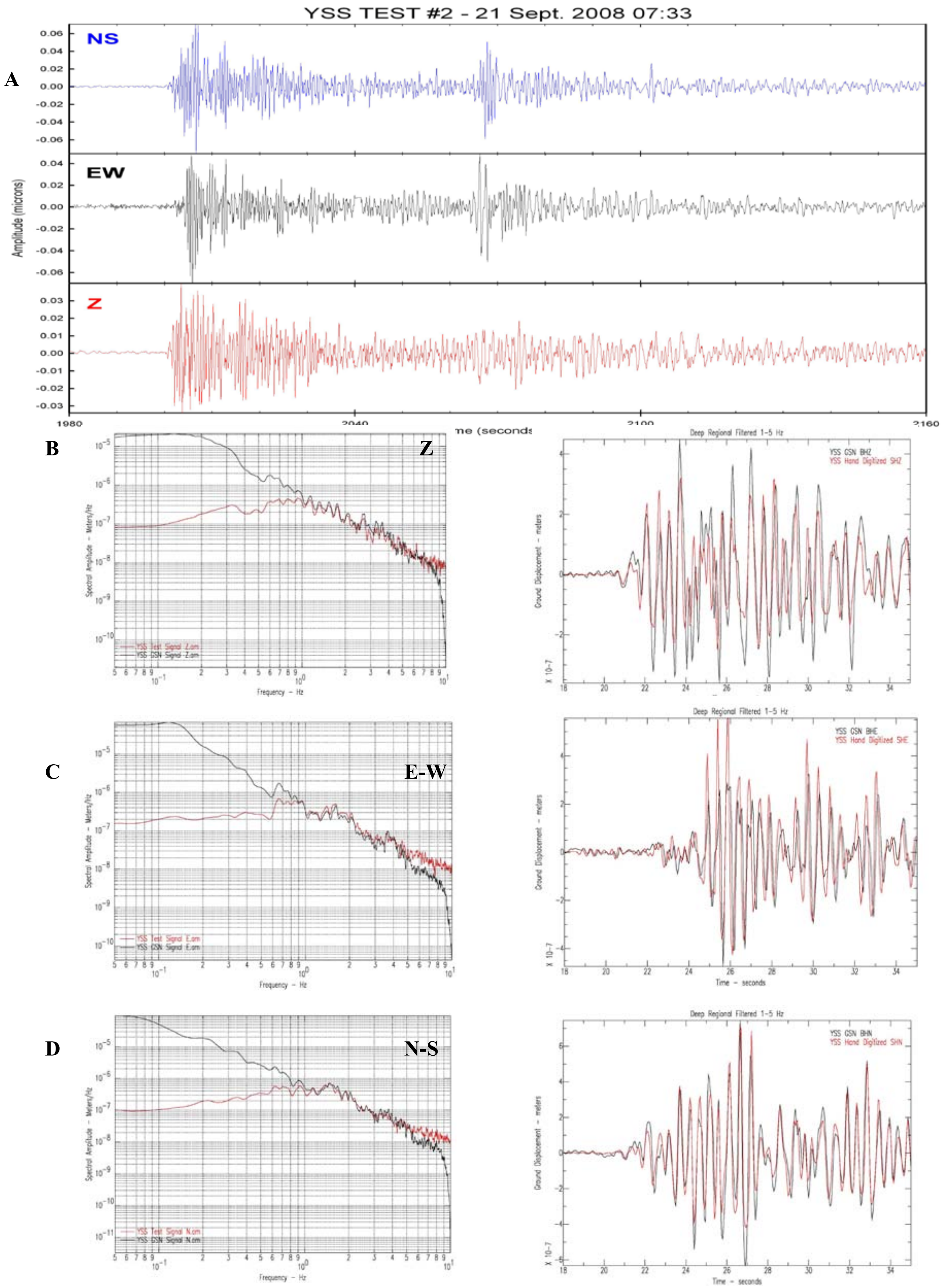

Figure 4. A. Hand digitized SP waveforms of a 21 Sept. 2008 regional earthquake recorded on photo paper at Yuzhno Sakhalinsk. B-D. Comparisons of frequency responses (left) and 1-5 Hz filtered waveforms (right) of the digitized data to GSN data from the co-located IRIS station (YSS). Components are, top to bottom, Z, E-W, and N-S.

Nuclear Explosion Discrimination

The digitized seismograms produced in this study allow the first possibility of using digital seismic data to develop seismic discriminants for many regions of the former Soviet Union as well as at specific stations. Many of the stations for which we are digitizing seismograms are now GSN or CTBTO sites, but did not become so until after cessation of most testing, thus there is no digital base of nuclear explosion records. Most of the GSN or CTBTO stations are situated at the longer-running, historic station sites that have the most extensive archives of PNEs.

A comparison of the 23 July 1987 Neva 2-2 PNE (15 kt; m_b 5.1) and a southern Yakutia earthquake (26 April 1994; m_b 5.3) as recorded at Yakutsk (Figure 5 inset). The PNE is digitized to 20 sps from the short period analog record, and the earthquake is from the digital GSN station (YAK). Seismograms are plotted both as raw data (Figure 5 top) and with a 4 Hz high pass filter (Figure 5 bottom). In both cases, relative Lg/P amplitude ratios are high for the earthquake (green) and low for the PNE (red).

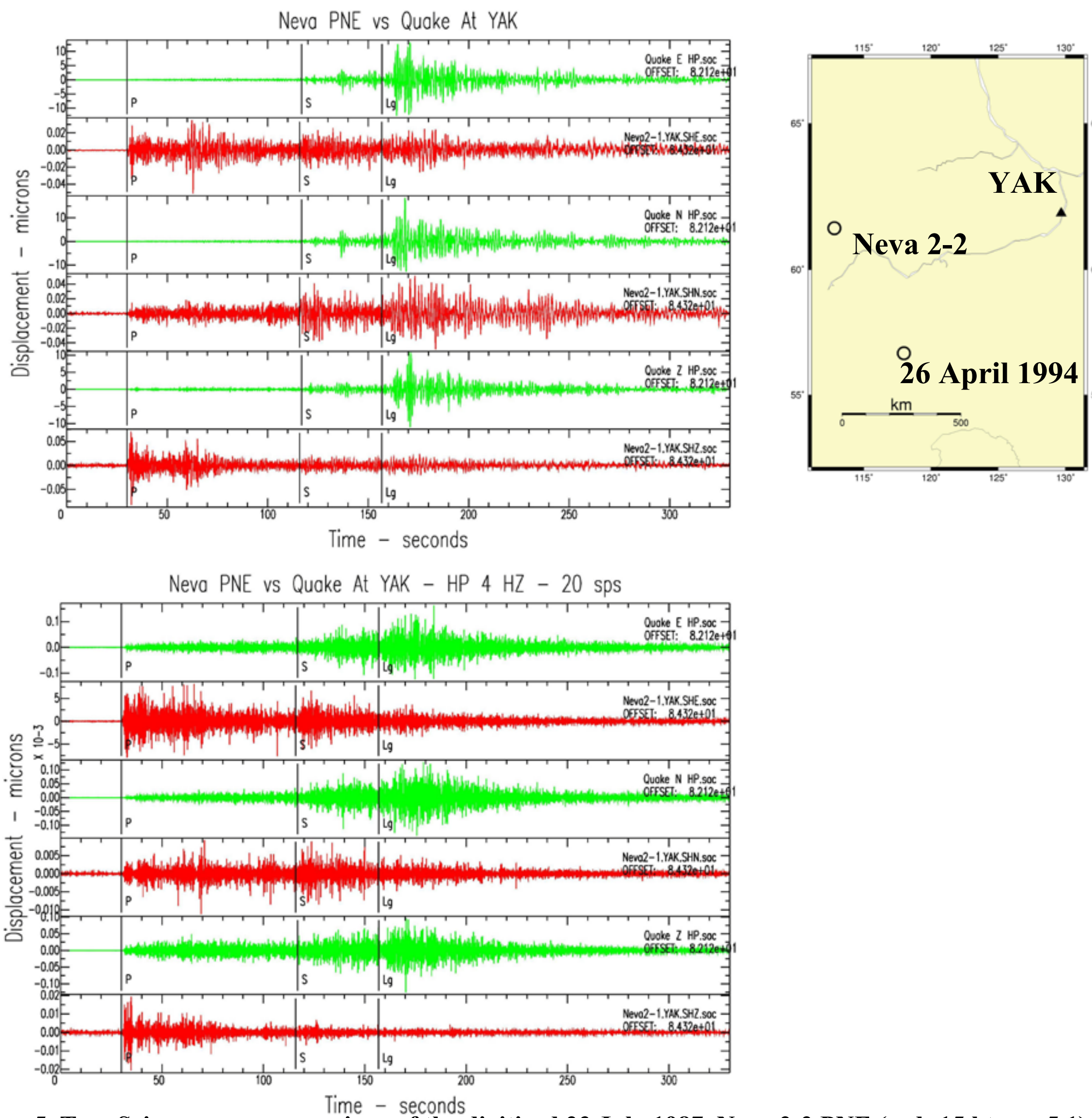

Figure 5. Top. Seismogram comparison of the digitized 23 July 1987, Neva 2-2 PNE (red; 15 kt; m_b 5.1) and a southern Yakutia earthquake (green; 26 April 1994; m_b 5.3) as recorded at Yakutsk. Bottom. The same seismograms with a 4-Hz high pass filter applied. In both cases, the differences in the Lg/P ratios can discriminate the events. Locations of the PNE, earthquake, and station Yakutsk (YAK) shown on map.

Seismic Record Sections

The distribution of seismic stations and PNEs allow seismic record sections to be produced, both as a multiple source composite as well as a single source profile. Using the Neva PNEs, we produce three specific profiles (Figure 6). The Magadan and Chukotka profiles extending eastward are the first extension of the PNE profiles through this area. The Magadan profile (Figure 7) indicates velocities essentially identical to those from the Kimberlite-4 profile in the Siberian Platform, which includes stations Yakutsk and Khandyga. The Siberian Platform portion of the Magadan profile intersects the Kimberlite-4 profile between the Neva site and station Yakutsk, thus our result is consistent. Velocities drop relative to Kimberlite-4 at station Nezhdaninsk located in the Verkhoyansk fold and thrust and the first profile station located off the Siberian Platform. Relative to iasp91 (I-91), velocities in the western portions of the Magadan profile associated with the Siberian Platform and western Verkhoyansk Fold Belt are elevated relative to I-91. Beyond the platform in the tectonically active areas, velocities are reduced and closer to I-91. The Chukotka profile (Figure 8) shows elevated velocities relative to I-91, which quickly decreases at station Zyryanka on the Kolyma-Omolon Super Terrane. The delayed *P* arrival may be an effect of the large Zyryanka Basin in the vicinity of the station. Continuing east through Chukotka, velocities are much closer to I-91. The Altai profile (Figure 9) shows velocities consistently elevated relative to I-91, which may be a result of paths contained almost entirely within the Siberian Platform. A sample composite record section from many PNEs as recorded by Altai-Sayan network stations is shown in Figure 10. The composite record section is representative of the Siberian Platform.

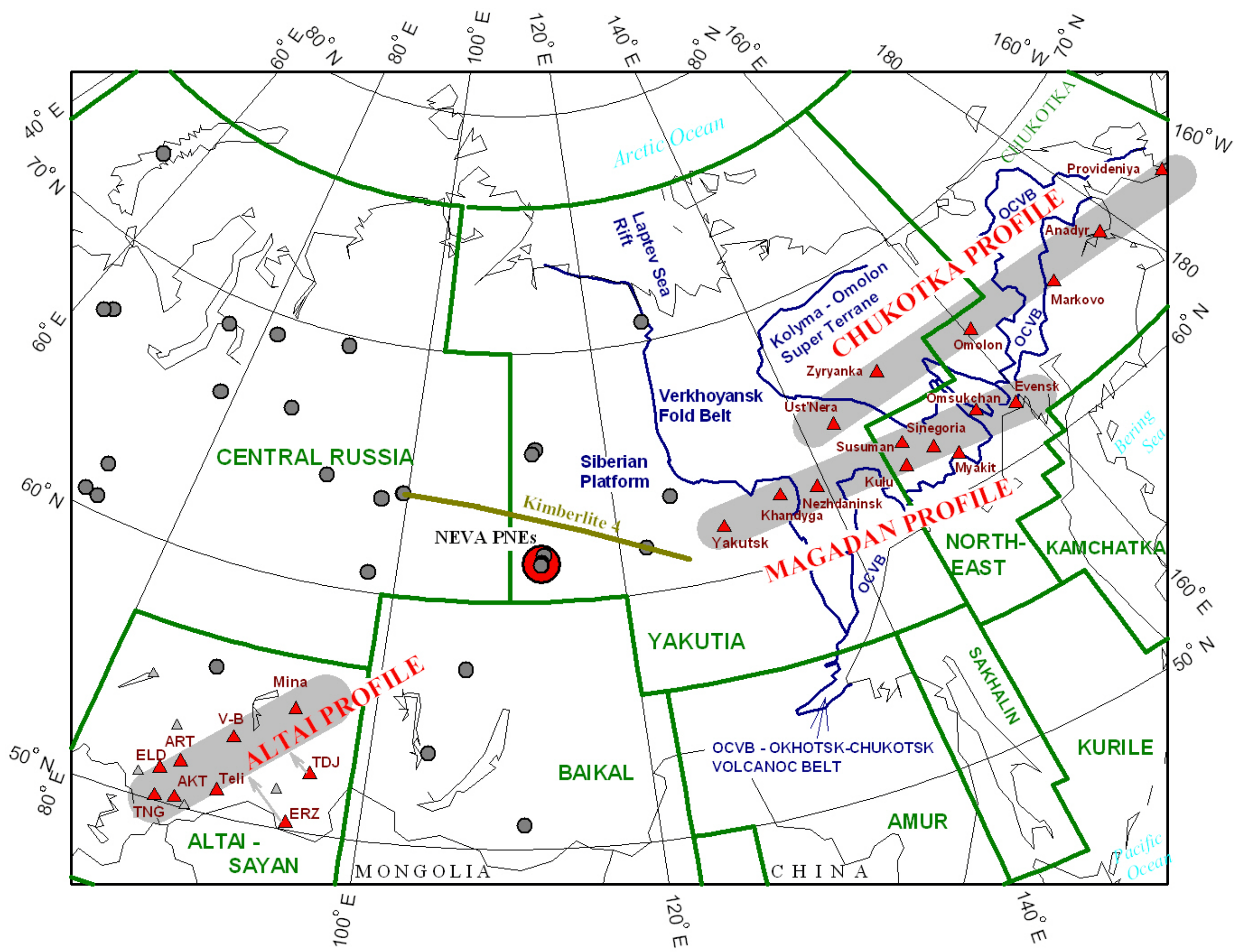

Figure 6. Index map of record sections displayed in Figures 7-10 class. The Magadan, Chukotka, and Altai profiles all use data from the Neva PNEs with stations used shown in red and labeled. The composite record section in Figure 10 used PNEs throughout Siberia (gray dots) and all stations of the Altai-Sayan seismic Network (all triangles in that region). Seismic networks shown and named in green and generalized tectonic provinces in the Russian Far-East shown in blue.

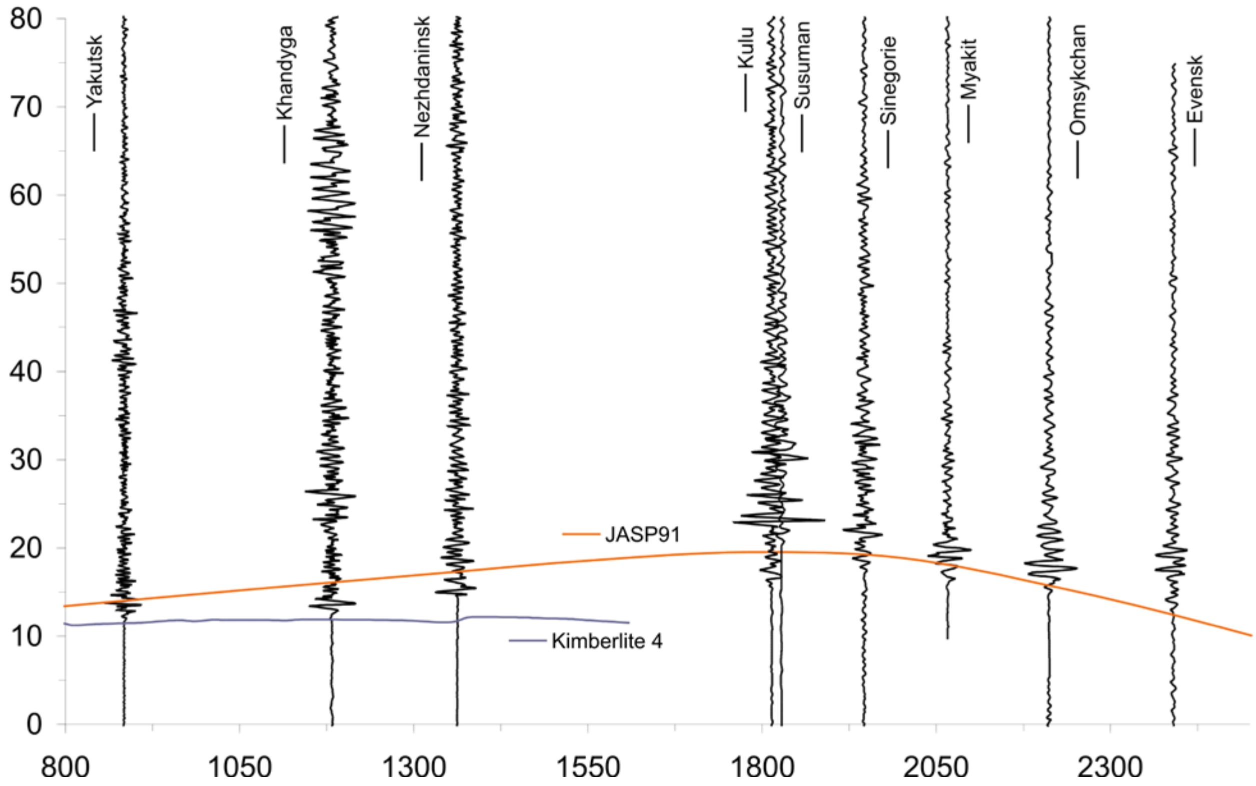

Figure 7. Record section crossing the Magadan region from the Neva PNEs. Reduction velocity is 9.0 km/sec.

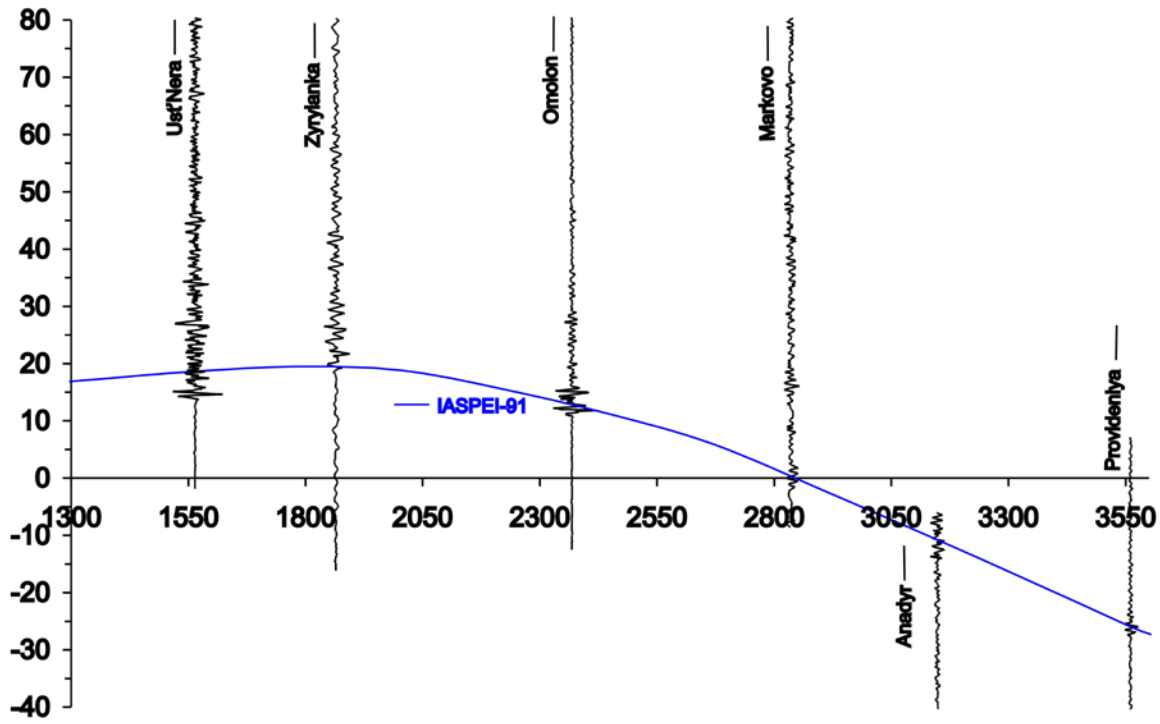

Figure 8. Record section crossing Chukotka from the Neva PNEs. Reduction velocity is 9.0 km/sec.

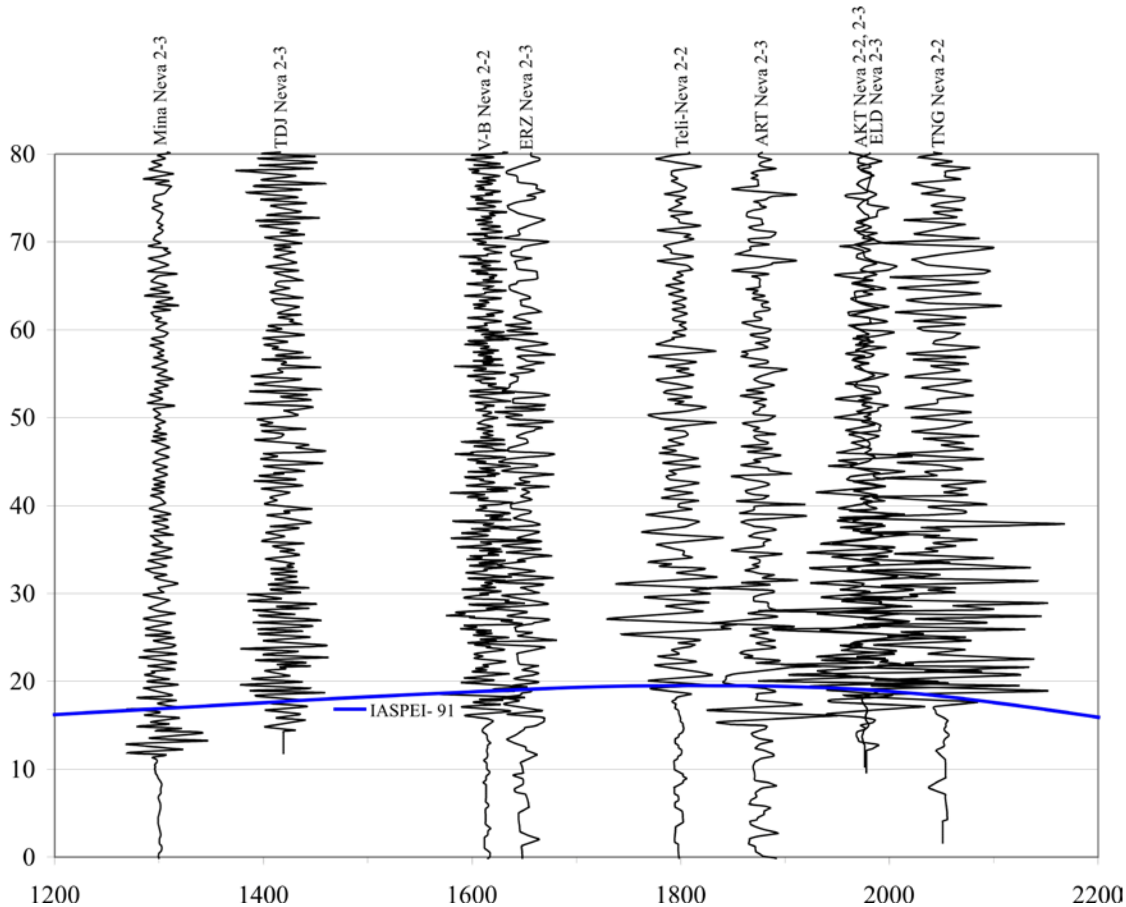

Figure 9. Record section crossing the Altai region from the Neva PNEs. Reduction velocity is 9.0 km/sec.

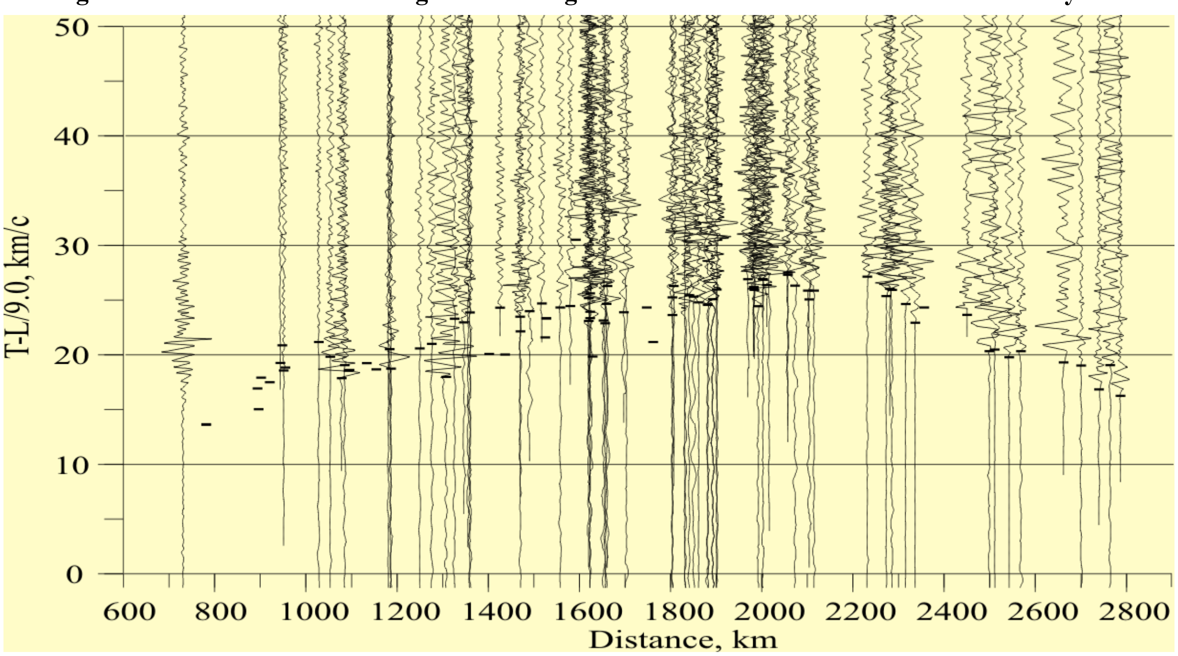

Figure 10. Composite record section using PNEs from throughout Siberia as recorded by the Altai Sayan seismic network. This section is representative of the Siberian Platform. Reduction velocity is 9.0 km/sec.

CONCLUSIONS AND RECOMMENDATIONS

The historic photo paper seismograms of PNEs conducted in the Soviet Union represent a large data set that remains to be fully exploited. These data can be useful for nuclear explosion discrimination, velocity studies, etc. at stations and in areas not previously researched. It is possible to digitize these seismograms to obtain digital seismograms compatible with more advanced computer based analysis. Digitization of the seismograms, most of which are short period, does a very good job of frequency/amplitude recovery in the 1–5-Hz range. Analysis of the deviation of observed travel time from the I-91 curve appears to correlate with tectonic settings and crustal structure.

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