SEISMIC CALIBRATION AND DISCRIMINATION IN NORTHEAST RUSSIA

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ABSTRACT

In an effort to obtain ground truth (GT) classifications in support of nuclear explosion monitoring for continental regions of northeastern Russia, we relocated and assigned GT classifications to 118 seismic events reported in the International Seismological Centre (ISC) supplemented with previously unavailable local data. Of the relocated events, 26 events are classified as GT10. From these events, consistent patterns of residuals, essentially source-specific station corrections (SSSC's), show upper mantle velocities are elevated under the Siberian platform and slower below the northern Sea of Okhotsk.

To further improve calibration capabilities in northeast Russia, we have been analyzing data from a small network of digital seismic stations deployed in the Magadan region. The stations are located close to areas of both tectonic seismicity and active mining, thus record signals from both. We have been undertaking routine phase time picking and hypocenter determination of both local and near regional seismic events and confirmed/suspected mine explosions.

Using waveforms of both tectonic events and mine blasts, we have begun the process of explosion discrimination using amplitude ratios of various Lg frequencies. Preliminary results indicate that the ratio Lg(4-8Hz)/Lg(0.75-1.5Hz) using peak amplitudes may not be sufficient to discriminate mining explosions from earthquakes in northeast Russia. Additional, more comprehensive research is underway.

We have undertaken efforts to acquire improved ground truth data for both earthquakes and explosions. In January 2001 two moderate earthquakes occurred approximately 100 km west of Magadan. We deployed two temporary stations to investigate the aftershock sequences of both events. About 15 events were locate-able although several more were recorded. To obtain ground truth data for explosions, we have deployed temporary stations and recorded quarry blasts near Magadan, and are currently undertaking an experiment to record explosions at a coal mine several hundred kilometers north of Magadan.

KEY WORDS: GT classification, ground truth, explosion discrimination, northeast Russia

OBJECTIVE

The objective of our research is to improve epicentral coordinates to better locate and identify ground truth seismic events in northeast Russia in support of Comprehensive Nuclear-Test-Ban Treaty (CTBT) monitoring A second aspect of our research to improve CTBT monitoring capability in northeast Russia is to deploy a network of digital stations for obtaining ground truth events and using waveform characteristics for event discrimination.

RESEARCH ACCOMPLISHED

GT Classified events

In effort to obtain ground truth (GT) classifications in support of Comprehensive Nuclear-Test-Ban Treaty monitoring for continental regions of northeastern Russia, we have relocated 118 seismic events reported in the International Seismological Centre (ISC) catalog which occurred from 1970 through 1997 (Figure 1). ISC solutions for this region utilize data from very few local or regional stations. In this study, we have supplemented ISC data with local and regional arrivals from Russian regional seismic networks. Local unpublished data from the bulletins of the Kamchatka, Magadan, Yakutsk, Amur, Sakhalin, and Irkutsk networks were used. For many of the events, selected original seismograms were inspected to obtain arrival times not otherwise recorded. Often this was for stations in one network for an event which occurred within the area covered by another network, since data are not normally exchanged between networks.

In the process of combining local network data with ISC arrivals, it was found that for stations up to 10º distance, phases reported in ISC are sometimes misidentified. The most common misassociation is the secondary Pg or Sg phase identified as a Pn/P or Sn/S arrival. This misidentification of phases can result in poor hypocenter determinations by ISC, particularly for events with few receiving stations or poor azimuth distribution to stations. These errors arise due to the fact that arrival times and phases reported to the ISC for many of the Russian stations are the result of preliminary data analysis. The local data bulletins contain the final analysis of arrival times and phase associations. Also, in many cases, ISC reported times are rounded to the nearest second, while local bulletins report arrivals to a tenth of second. In both cases, local bulletin data take preference over that from ISC for relocations computed in this study.

Each event was relocated three times using combined local and teleseismic arrivals, only arrivals within 20º, and only arrivals within 10º. The specific location methodology uses locally calibrated crustal velocity travel time curves, which are discussed extensively in Mackey (1999), Mackey and Fujita (1999), and Mackey and Fujita (2000). To best evaluate which set of data produce the best locations, particular attention was paid to aftershock sequences, and how closely events cluster using the different data sets. Locations computed using only data either within 10º or 20º cluster best, although locations including local and teleseismic data are clearly improved over those from ISC alone. In general, for events with good azimuthal coverage of stations within 5º the best locations are those computed with only the local (<10º) and regional (<20º) data, while events having poor azimuthal coverage of close-in stations are better located by including teleseismic data. Based on the general distribution and residuals of stations, a preferred location was selected for each event analyzed.

All relocated events are assigned GT levels, with 26 events meeting or exceeding the GT10 criteria (e.g., Yang and Romney, 1999; Figure 1). A few events which formally met these criteria were excluded from our GT10 classification due to high station residuals for some close in stations, or other odd station distribution problems which can result in poor epicenter control. It should also be noted that many of our relocated events miss the formal GT10 criteria, but we suspect that the location determined here is within 10 km of the true epicenter based on proximity to fault traces, etc. Most of the remaining relocated events meet GT25 criteria. Although no events formally qualify as GT5, several events are likely within that accuracy

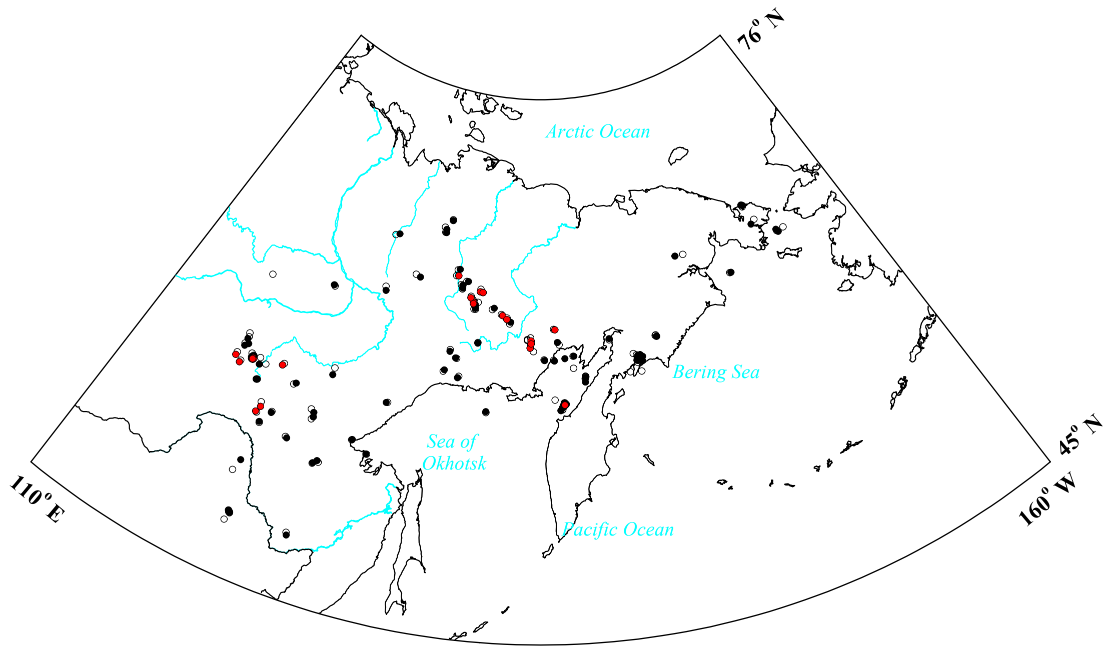

Figure 1. Comparison of ISC epicenters (open circles) and relocations (filled circles). Red filled (grey) circles represent relocations that meet or exceed GT10 criteria. Note that relocations cluster tighter and form better lineaments near the center of the figure.

Travel-time variations in northeast Russia

To further improve epicentral locations by determining station dependent path corrections, we investigated travel-time residuals relative to JB at nine regional stations from events in northeast Russia. The stations had epicentral distances from the events of about 1 - 20E.

The results for Tiksi (TIK, TIXI; Figure 2), based on all the events studied, are characteristic. High negative residuals, indicating fast velocities, are observed from events in south Yakutia. These rays pass through sub-Siberian shield mantle, which is expected to have higher velocities. Slightly negative residuals are obtained from the Chersky Range, indicating some higher velocity upper mantle exists in the region of the Kolyma-Omolon superterrane. Events from the eastern Sea of Okhotsk and Koryakia have somewhat positive residuals, and suggest that there may be slower mantle due either to lithospheric rifting (Penzhina and Parapol basins; Worrall et al., 1996) or to effects of the supra-subduction mantle wedge. Similarly, a few events with slightly positive residuals in northeast Amur District may be related with extension along the western Sea of Okhotsk (Shantar-Liziansky basin) also proposed by Worrall et al. (1996). One event in the Yana River valley gives a high positive residual which may be related to the present or recent extension of the Arctic Mid-Ocean ridge into the continent. The restricted number and distribution of GT10 events provides only information from southern Yakutia and the Chersky Range, but leave no doubt as to the faster velocities to Tiksi from those two regions. Travel paths under the Siberian platform to Norilsk yield consistently negative residuals of a magnitude similar to those at Tiksi.

Arrivals at Yuzhno Sakhalink confirm that ray paths through the sub-northern Sea of Okhotsk mantle yield high positive residuals (Figure 3). Events from the Amur region with origins in the Siberian platform west of the proposed rift again yield slightly positive residuals, suggesting that their respective higher and lower velocities tend to cancel out each other. All arrivals at Petropavlovsk are late, indicative of passage through the supra-subduction zone upper mantle. Similar to Yuzhno Sakhalinsk, as events occur farther into the higher velocity

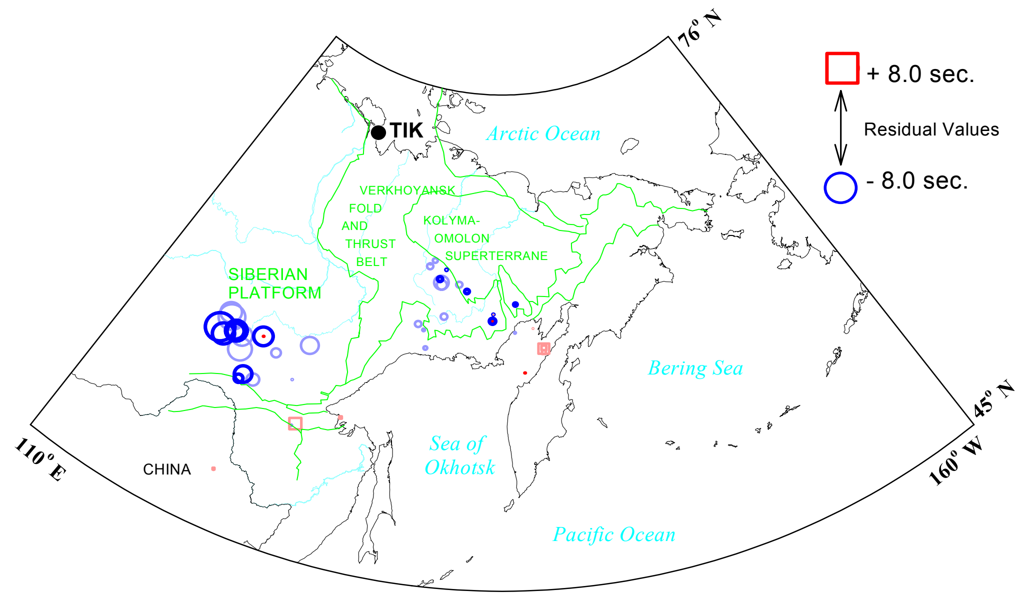

Figure 2. Residuals for arrivals received at Tiksi (TIK, TIXI). High negative residuals from the south of Tiksi indicate higher than average velocities under the Siberian platform. Velocities associated with the Verkhoyansk fold and thrust belt indicate only slightly elevated seismic velocities. Heavier shading indicates GT10 events.

Siberian platform relative to Petropavlovsk residuals become less negative.

Bilibino also yields slightly positive residuals from the northern Sea of Okhotsk and negative residuals for the Kolyma-Omolon superterrane and Koryakia, suggesting that upper mantle velocities in far northeast Russia are slightly fast. Peleduy, however, yields late arrivals from the Kolyma-Omolon superterrane. Arrivals from the northern Sea of Okhotsk are again late, and early arrivals are observed on Siberian platform crossing paths from the Verkhoyansk Range.

Residual patterns for Seymchan and Magadan are similar. The arrivals from Shelikhov Bay (northeast Sea of Okhotsk) and the Amur region are again all late, while a mix of residuals is observed from the Chersky seismic belt. From these stations, Chukotka paths are slightly slow. Finally, Yakutsk shows a wide mix of arrivals with generally early arrivals from the Aldan shield and the Verkhoyansk Range and very late arrivals from Shelikhov Bay and Chukotka.

Taken as a whole, it is clear that ray paths traversing the upper mantle under the Siberia platform are fast, while those originating from, or traversing, the supra-subduction zone or rift regions of the Sea of Okhotsk are very slow. There is an indication of low velocities under the northern Amur district, although this is less distinct. Velocities under Chukotka are less certain. The situation in the Chersky Range is also less clear, although ray paths traveling greater distances may be marginally faster than those to nearby stations. These observations will help in constraining upper mantle velocities and indicate that future development of Source Specific Station Corrections (SSSC's) may yield positive results.

Regional network deployment

We continue development of our digital station network in northeastern Russia to improve epicenter locations

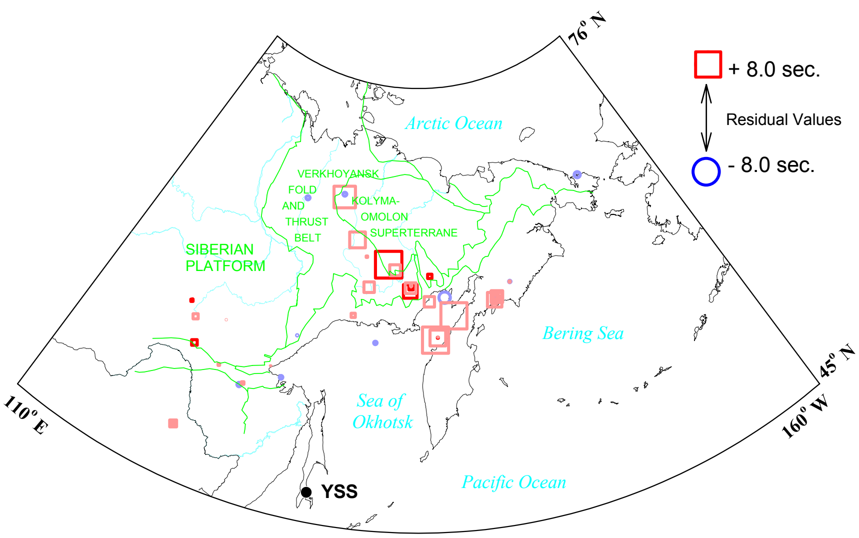

Figure 3. Residuals for arrivals received at Yuzhno Sakhalinsk (YSS). Heavier shading indicates GT10 events.

and begin a program to develop seismic discriminants for CTBT monitoring by digitally recording local explosions and earthquakes. To obtain better records for study, we began converting existing photo paper analog stations in the Magadan and Yakutsk networks to digital data acquisition. At present, we have seven stations deployed in northeast Russia, most in the Magadan region (Figure 3). Since the initial deployment, a couple of stations have had to be moved due to logistical reasons. We have also deployed a few stations in temporary locations for the purpose of recording small aftershock sequences (Talon and Tauisk) and known mine explosions (Tal'Yuryakh). Approximately 170 earthquakes have been located by the network since January 2000, although many more smaller events are locate-able with additional analysis. All stations are 3 component, with three stations recording broadband instruments (Seymchan - STS-1, Okhotsk - Guralp CMG-40T, and Omsukchan - CMG-40T). The remaining stations use short-period Russian seismometers (SKM-3 or SM3-KV). All seismometer outputs are digitized at 30 samples per second with 24-bit resolution and logged on a PC. In addition, we are supplementing our digital data with records from the IRIS station at Magadan, MA2, and other regional analog photo paper stations.

Explosion ground truth and discrimination

We have recorded mine blasts from many locations throughout our study region with yields ranging up to or exceeding 40 T. To obtain ground truth information on explosions, we have either visited or deployed a temporary station at mine sites to obtain information on blast size and location. Figure 5 depicts a seismogram of one of several 40 T blasts which occurred near Neksikan in April/May 2001, about 20 km southwest of the station in Susuman. On this seismogram, note the large amplitude Rg component, as well as a clear infrasonic arrival about 70 s after Pg. Lg arrivals from several of the Neksikan blasts were recorded at Magadan (MA2) and our farthest station, Okhotsk, over 400 km distant (Figure 6). Lg arrivals recorded at Magadan and Okhotsk are characterized by low frequency arrivals (0.7-1.5 Hz) with higher frequencies (4.0-8.0 Hz) being absent or completely obscured by background noise.

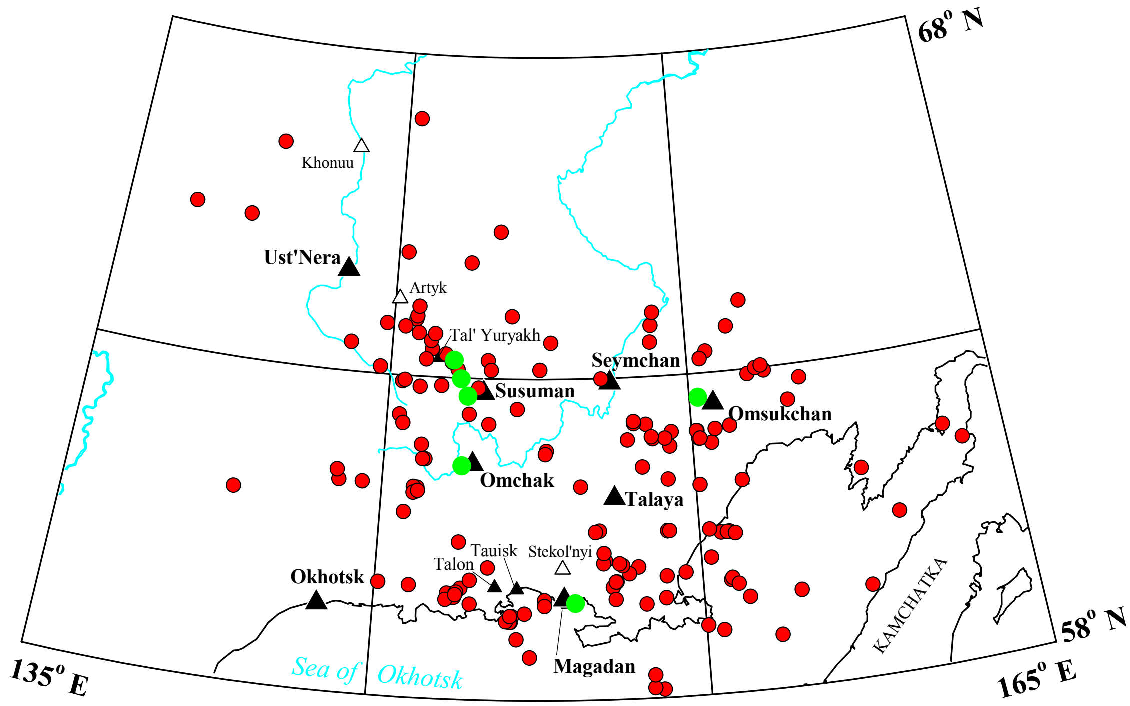

Figure 4. Digital seismic network deployed by Michigan State University in eastern Russia (permanent stations - large black triangles, temporary stations - small black triangles, and supporting analog stations - white triangles). Also shown are earthquakes located from January 2000 through May 2000 (small red circles) and explosion sources (large green circles).

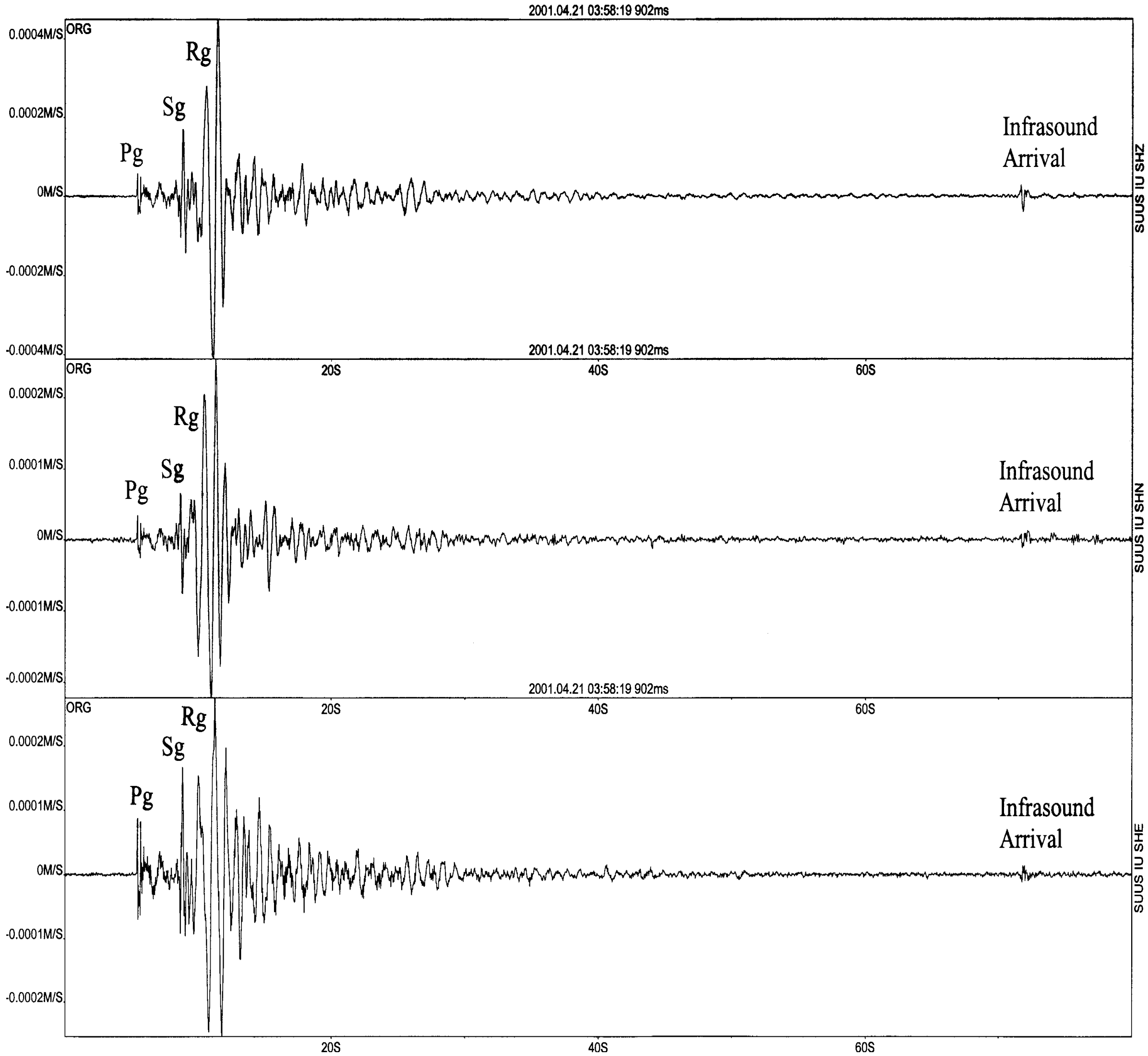

Figure 5. 3-component seismogram (top - Z, middle - N-S, bottom - E-W) of a 40,000-kg explosion recorded at Susuman. This blast occurred April 21, 200, in a placer gold mine near the town of Neksikan, about 21 km southwest of Susuman. Note the clearly developed Pg, Sg, and Rg arrivals, as well a clear infrasound arrival recorded on all seismometer components about 70 seconds after Pg.

As we have recorded a large number of

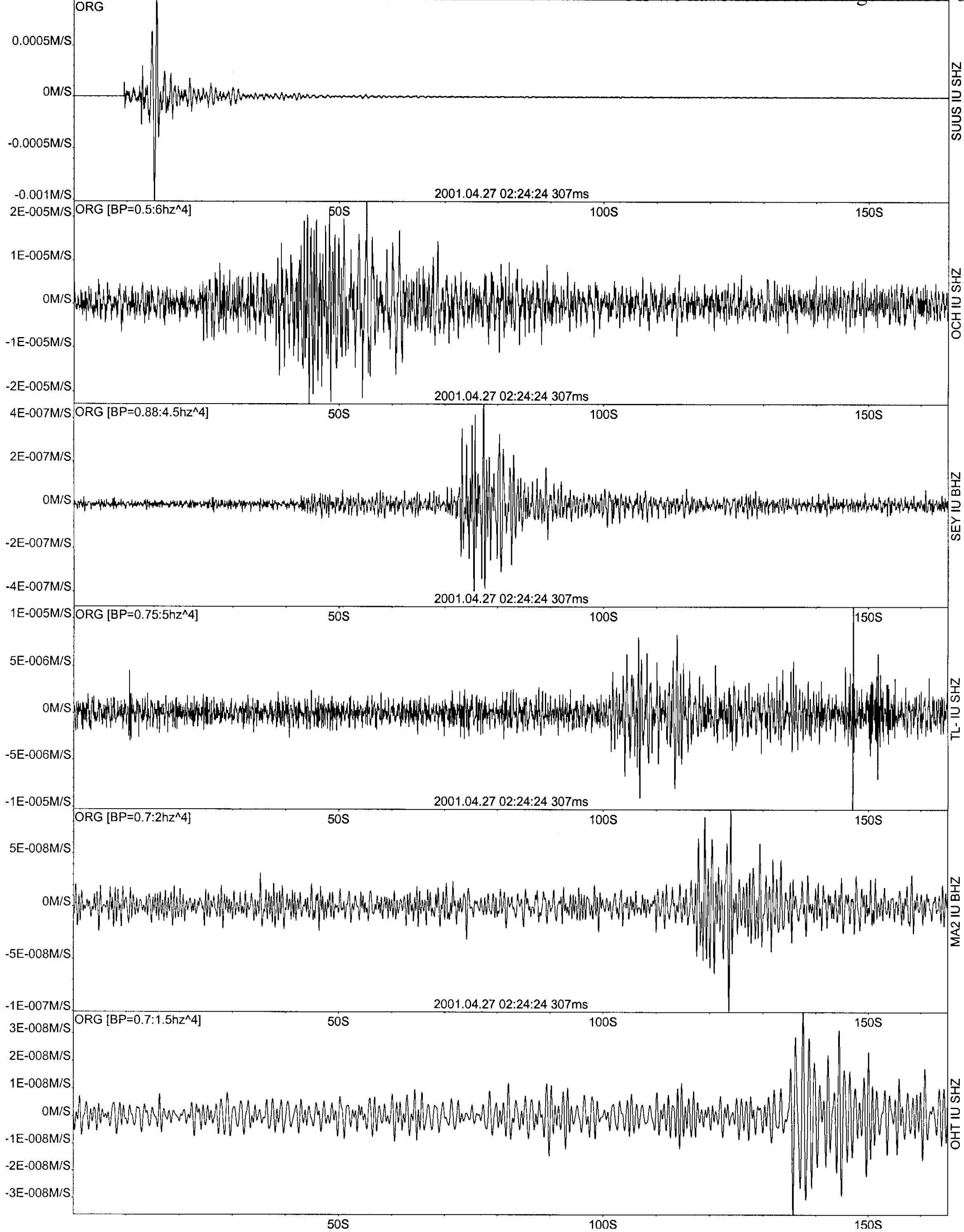

Figure 6. 40,00-kg blast of April 27, 2001, as recorded by several of our stations (top to bottom: Susuman (22 km), Omchak (111km), Seymchan (236), Talaya (297 km), Magadan (MA2; 381 km), and Okhotsk (441 km). Note the well developed low-frequency Lg arrival at Okhotsk. All records except Susuman are bandpass filtered.

earthquakes and explosions at throughout the study region. We can attempt to discriminate between explosions and earthquakes using various Lg amplitude ratios. Preliminary results indicate that the ratio Lg(4-

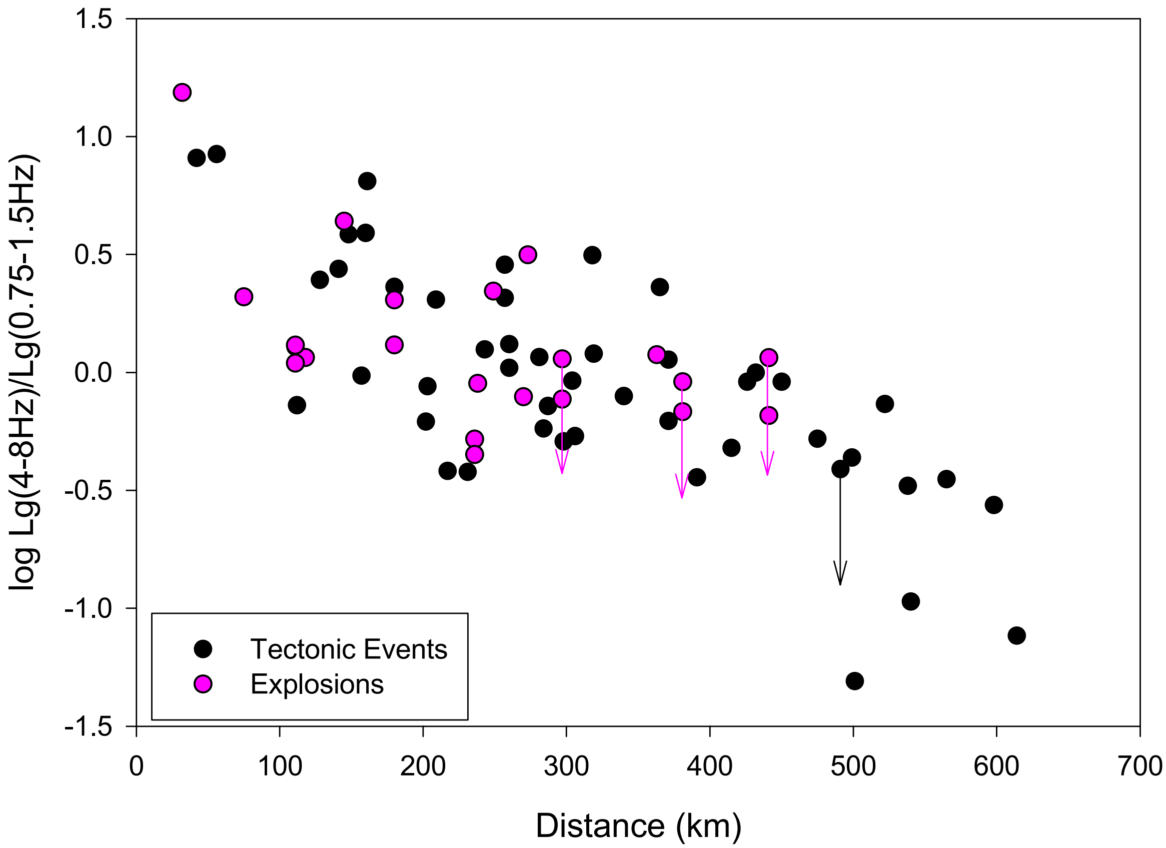

Figure 7. Composite plot of Lg spectral ratio vs. distance for tectonic events and explosions. Lg amplitudes used were maximum peak to peak. This plot contains data for all deployed stations (including MA2, but excluding Omsukchan, which was deployed July, 2001). There is no apparent difference in the plotting of earthquakes and explosions; thus, discrimination is not possible by using this method in this region at these distances. Points with arrows represent maximum possible ratio for arrivals with a clear low-frequency Lg arrival (see Okhotsk, Figure 6) but no apparent high-frequency arrival. In this case, the high-frequency Lg is substituted with the high-frequency background noise amplitude.

8Hz)/Lg(0.75-1.5Hz) using peak amplitudes is not be sufficient to discriminate mining explosions from earthquakes for local and near regional distances (<500km) in northeast Russia (Figure 7). In general, the overall relationship (slope and intercept) between earthquake Lg ratios vs. distance is nearly identical to that of HIA (Hartse, 2000). It should be noted that this represents only the most simple approach to an Lg discriminant for northeast Russia. Additional more comprehensive research is underway to look at the RMS amplitudes of the full Lg wave packet (Hartse, 2000) as opposed to peak amplitudes. Additional phase amplitude ratios (Pg/Lg, Pn/Lg, etc.) will also be investigated.

CONCLUSIONS AND RECOMMENDATIONS

Use of regional and local phase arrival data has greatly improved epicentral coordinates in northeast Russia and should also provide SSSCs when analyzed in detail. Combined with the identification and removal of anthropogenic sources, this will greatly improve our monitoring capability as well as our understanding of the baseline natural seismicity of the region.

The deployment of digital recording systems has opened the possibility of explosion discrimination studies in northeast Russia. A large number of chemical explosions from known mines have been recorded by our network which contributes ground truth information to improve travel-time curve calibration and explosion discrimination. In contrast to northern China and south central Siberia (Hartse, 2000), preliminary results indicate that high frequency/low frequency Lg ratios are insufficient for discrimination purposes in northeastern Russia. Further analysis is underway. Continued study of waveform characteristics will be critical to the discrimination process and will further enhance our ability to discriminate natural earthquakes from explosions throughout the study area. To see if these results are characteristic only of the Magadan district or of northeast Russia as a whole, additional field deployments throughout the region are required.

ACKNOWLEDGMENTS

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