EVENT RELOCATIONS AND SEISMIC CALIBRATION IN NORTHEAST RUSSIA

Kevin G. Mackey and Kazuya Fujita

Department of Geological Sciences, Michigan State University

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

Contract DTRA01-98-C-0168

ABSTRACT

In effort to obtain ground truth classifications in support of Comprehensive Nuclear-Test-Ban Treaty monitoring for continental regions of northeastern Russia, we have relocated approximately 100 seismic events reported in the International Seismological Centre (ISC) catalog, which occurred from 1970 through 1996. 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 () < 20E) arrivals from Russian regional seismic networks. Supplemental data normally include Pn, Sn, Pg, and Sg phase arrivals. Pg and Sg phases are often reported out to 1,000 km, well beyond the Pn/Pg crossover distance. Relocations were computed using a least squares method utilizing Pn, Pg, and Sg arrivals. For the Pg and Sg crustal phases, locally calibrated velocities were utilized. The J-B travel-time curve was used for Pn arrivals, as it results in overall reduced RMS residuals when compared to the IASPEI 91 tables and generally agrees with the average crustal and upper mantle seis mic velocities and crustal thickness. Only stations within 20^{o} were used in the relocations.

Most of our relocations differ by about 30 km or less relative to ISC parameters, with some exceptions being considerably more (one event moved 500 km). Overall locations appear to improve: locations occurring within aftershock sequences cluster tighter, and event alignment with known active faults improves. There is no consistent pattern to the azimuth of change in epicenters from ISC to our relocations. However, locally, or within aftershock sequences, there is a consistent bias in the in the epicenter shift. No specific areas stand out as having large differences between ISC and our solutions.

In order to further improve calibration capabilities in northeast Russia, we have deployed a small network of digital seismic stations in the Magadan region, concentrated primarily in the Kolyma gold mining district. The stations currently have a spacing of about 200-250 km and are located in close proximity to areas of tectonic seismicity as well as active mining with associated explosions. Both microearthquakes and mine blasts are well recorded by our network. Expansion of the network is currently in progress.

Key Words: seismic regionalization, calibration, location, seismic sources

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. Northeast Russia is a tectonically complex region formed by the amalgamation of a large number of terranes of various origins in the Mesozoic and Cenozoic (Fig 1; Nokleberg et al., 1994). Thus, the crustal structure and seismic velocities are expected to vary considerably within the region. In addition, a presumed Pliocene rift system, the Moma rift, crosses the continental part of northeast Russia, while the Arctic Ocean shelf is traversed by the currently active Laptev Sea rift system (e.g., Fujita et al., 1990; Drachev et al., 1998). These rift systems have also perturbed the crust resulting in lower seismic velocities and thinner crustal thicknesses (e.g., Kogan, 1974; Mackey et al., 1998).

To accomplish our objectives, we have calculated travel-time curves specific to discrete cells in the study area. These individual travel-time curves were then used to relocate seismic events, both explosions and earthquakes, and compare them to known mining sites or epicenters calculated by international agencies (e.g., the International Seismological Centre, ISC), as well as Russian determined epicenters.

These velocity calibrations and relocations are based on a computerized database containing phase arrival times from approximately 10,000 historic earthquakes that have been located by several regional seismic networks in northeastern Russia, generally covering the past 30 years. Each network has utilized different location methodology, travel-time curves, and phase data (see Mackey and Fujita, 1999). Thus hypocenter determinations throughout the study area can be improved by using a standardized methodology, calibrated travel-time curves, and combining phase data from adjoining networks. In this paper, the larger events in the study area are relocated in conjunction with developing best-fit crustal travel-time curves.

This study will aid in improving ground truth information and in the identification of seismic sources throughout the study area.

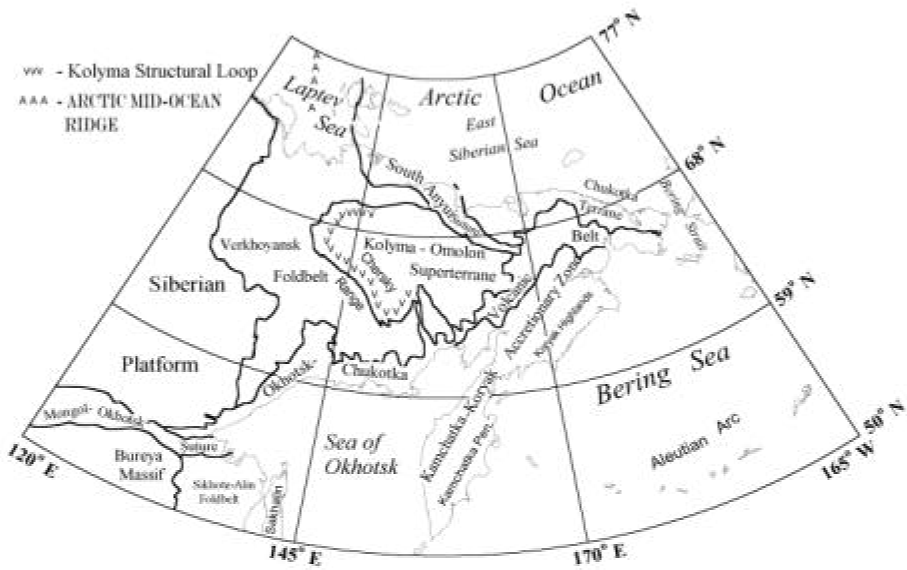

Figure 1. Index map and geologic provinces of northeast Russia.

RESEARCH PERFORMED

Relocations using Russian phase data

The basic location routine used is a least squares best fit routine, modified for this study to accept multiple phases, specifically Pg, Pn, and Sg. Sn arrivals are not used, as the data are considerably noisier than the other phases.

Throughout the study area, many geologic and tectonic environments exist. Combined with the physical vastness of the region, this makes it likely that no single velocity or travel-time curve will reflect actual seismic velocities for any particular phase. In order to overcome this problem, the study area was broken into cells, and the best fitting velocities were determined by minimizing the sum of event RMS residuals through trial of multiple travel time curves. Cell sizes are generally 3^o north-south by 5^o east-west, although this was adjusted in areas with sparse activity in order to increase the number of useable events. For any given block, only events containing Pn phase arrivals (generally 2 or more) were used. This selects only the larger events, which contain more arrivals and have better azimuthal coverage of receiving stations. The number of selected events ranged from 5 to over one hundred, with a few exceptions.

Travel-time curves for Pg and Sg phases were calculated assuming a flat-earth-straight-ray approach. This is reasonable because Pg and Sg phases are confined to relatively short distances in the crust, thus the distance traveled between epicenter and station is considered equivalent to the surface distance. For hypocenters at depth, the travel path is assumed to be the hypotenuse of the triangle made by the depth and the surface distance. Event depths are restricted to a maximum of 33 km, as all events are assumed crustal in nature. Events for which depth tends above the surface are restricted to 0 km.

In order to determine the best crustal velocities for locating events within a given cell, the selected events are first located with crustal velocities 'guessed' for the region. The velocities used in the guess were generally the best-fit velocities froman adjacent cell. The resulting output is analyzed for high residual arrivals, generally those greater than 3.5 seconds. High residuals are generally a result of either typographical errors, misassociated phases, or bad time picks. Typographical errors and misassociated phases are corrected if possible, while bad time picks are omitted from use in further locations. Events having many high residual arrivals such that it was impossible to get a reasonably good location and events with four or fewer recording stations are omitted from further analysis. Overall, less than 5% of the originally selected events were omitted in the study area.

In order to determine the better fitting travel-time curve to use for Pn arrivals in the location procedure, the Jeffreys-Bullen (JB; Jeffreys and Bullen, 1970) P wave travel-time curve was compared to the IASPEI 91 (I-91) curve by Kennett (1991). Results for test regions in the Amur, northern Yakutia, Magadan, and Chukotka regions indicate that the JB table does a better job of fitting the Pn arrivals in the region. Therefore, the JB table was used in all relocations computed in this study.

Following removal of large residual time picks and correction of misassociated phases, the remaining selected events for a given block were located multiple times using different crustal velocities. A total of 1309 earthquakes were relocated in 44 geographic cells. Crustal velocities tested for each block range from 5.875 km/sec to 6.350 km/sec in 0.025 km/sec increments for Pg, and 3.470 km/sec to 3.650 km/sec in 0.020 km/sec increments for Sg. In this manner, the crustal velocities that best fit the events in the cell were found. The newly found best fitting velocity for each cell was then used to relocate the events a second time. After locating with the new velocity, any additional high residual arrivals were omitted or corrected. Arrivals with residuals over 3.0 seconds were removed. Arrivals with lower residuals were occasionally removed if the station was very close to the epicenter, or if a single residual had a value several times larger than all others for a particular event and 'stood out'. If any arrivals were removed or had phase associations changed, the events in the cell were again subjected to a search for the best-fit crustal velocities. Final Pg crustal velocities for each cell are shown on Figure 2. The distribution of Sg velocities shows a nearly identical pattern. Crustal velocities in northern Yakutia were somewhat problematic, with adjacent cells alternating between high and low velocities, which indicated that the original cell size used was exceeding the geographical scale of the velocity variations. Therefore, locations and calibrations for Yakutia north of 66^o were performed using a $5^o \times 3^o$ moving window, shifting the window in 1^o increments. For each cell, the best fitting crustal velocities were determined by trial of multiple Pg and Sg velocities as discussed above. This resulted in a similar velocity structure as determined earlier, but with greatly smoothed velocity shifts (Figure 2).

Velocity Structure

Crustal velocities determined in the location process correlate well with the regional tectonic provinces. Generally the highest velocities (Pg velocities ranging from 6.225 to 6.300 km/s and Sg from 3.61 to 3.65 km/s) occur in the western portion of the study region, which is part of the Siberian platform. Elevated crustal velocities in the Siberian platform are consistent with seismic studies conducted by Suvorov et al. (1999), where Pg velocities were generally found to range from 6.2 - 6.3 km/s. South of the Siberian platform, velocities decrease across the Mongol - Okhotsk suture (Figures 1 and 2). This velocity decrease is consistent with with the results of Suvorov

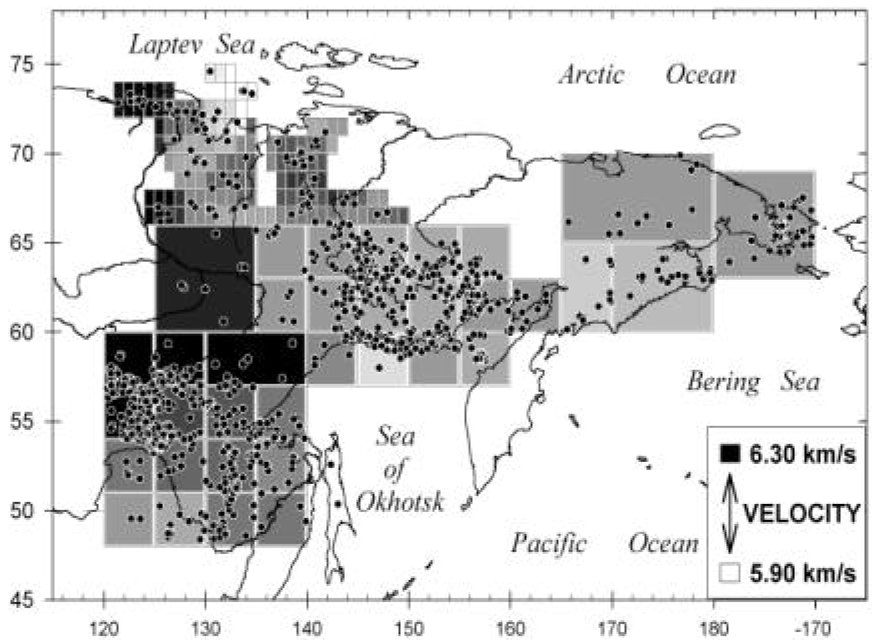

Figure 2. Grid of calibrated Pg velocities. Epicenters are shown for reference.

and Kornilova (1985). Velocities also drop sharply in the Verkhoyansk foldbelt, along the eastern edge of the Siberian platform. From the Verkhoyansk foldbelt and east through the Mesozoic terrane assemblages (Kolyma - Omolon Superterrane) to the Bering Strait, crustal velocities are consistently in the 6.00 - 6.05 km/s range, and Sg velocities in the 3.51 - 3.55 km/s range, with only a few cells deviating slightly. The final analysis for velocities in northern Yakutia indicates that the highest velocities are associated with the Siberian platform along the western edge of the region. The lowest velocities occur in the Laptev Sea and correspond to active rifting along the extension of the Arctic Mid-Ocean Ridge. The velocity shifts in northern Yakutia are probably a result of rapidly changing velocity gradients associated with presently and recently active rifting adjacent to the Siberian platform and other older tectonic structures. The low velocity region in the Laptev Sea extends into the continent, where it generally follows the strike of the grabens outlined in Fujita et al. (1990).

Location Improvements

The newly determined velocities in each cell were used in the final relocation of events. Plots comparing original and relocated epicenters show clear improvement of relative locations relative to the Russian network solutions. It is expected that an improvement in event locations will result in better defined lineations in the seismicity as earthquakes occur along faults, and that clusters of events would concentrate into smaller areas for near-point sources, such as aftershock sequences. In the Amur region, the seismicity trend extending through the Zeya basin becomes clearer and seismicity clusters tighten throughout the region (Figure 3). Relocated epicenters in the Magadan region show a tightening of several clusters of seismicity and a slightly improved lineation of events along the trace of the Ulakhan fault (Figure 4). The cluster near 62^o N x 157^o E is due to an aftershock sequence following an event on February 11, 1987. Clusters of seismicity in the eastern portion of Chukotka are reduced to much smaller lineations.

Travel-time curves resulting from the relocated events also show a distinct improvement. Figure 5 compares travel-time curves for one cell in the Magadan region. The level of scatter is reduced for all phases using the relocations, consistent with improved hypocenter parameters.

Comparison with ISC Epicenters

About 100 events among those that we relocated are listed in the ISC Bulletin. Most (90%) of our relocations differ by less than 45 km relative to the ISC parameters, with a few being significantly different (one event with poor station coverage in the ISC moved 500 km). As noted, our locations are likely to be an improvement

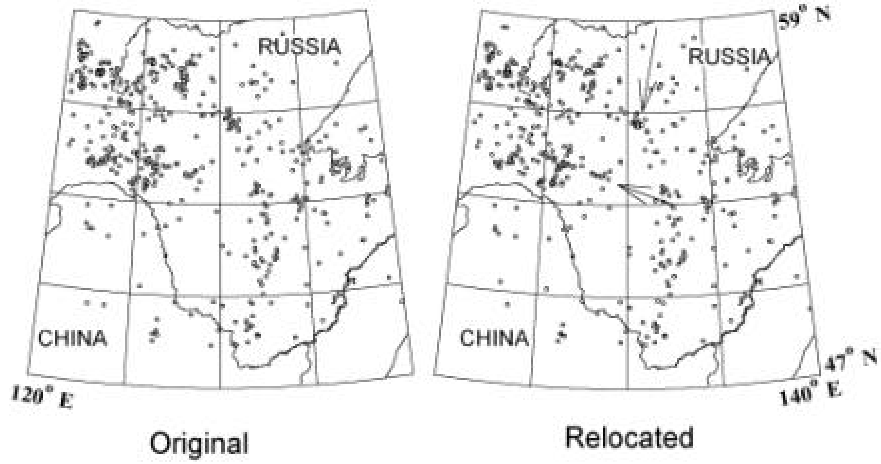

Figure 3. Original vs. relocated epicenters for the Amur region.

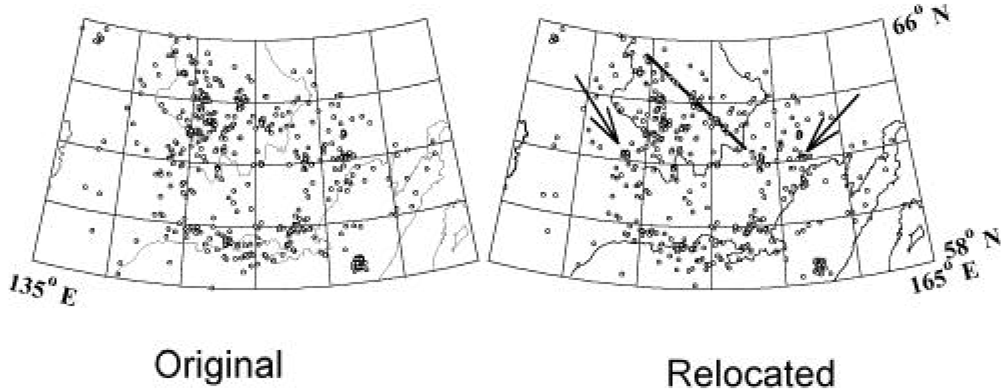

Figure 4. Original vs. relocated epicenters for the Magadan region. Ulakhan fault is shown by a heavy line.

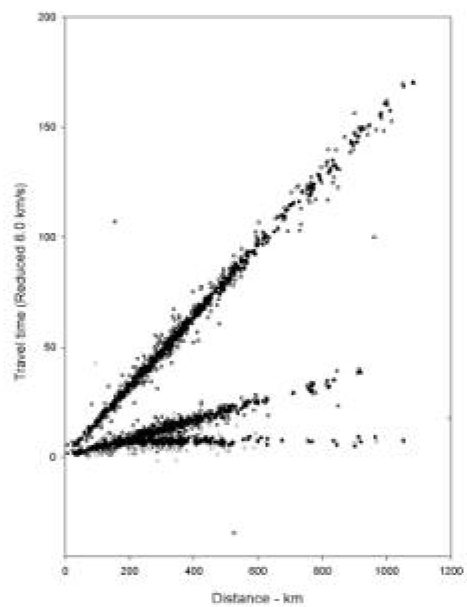

Figure 5. Travel-time curve for the region 60-63°N x 145-150°E comparing original (open circles) with relocated event parameters (closed circles). Note the significant reduction in scatter of data points. Sn data are omitted.

due to the large number of local phases utilized. However, there is no large-scale spatial pattern to the azimuth or magnitude of change in epicenters calculated by ISC relative to our relocations (Figures 6 and 7).

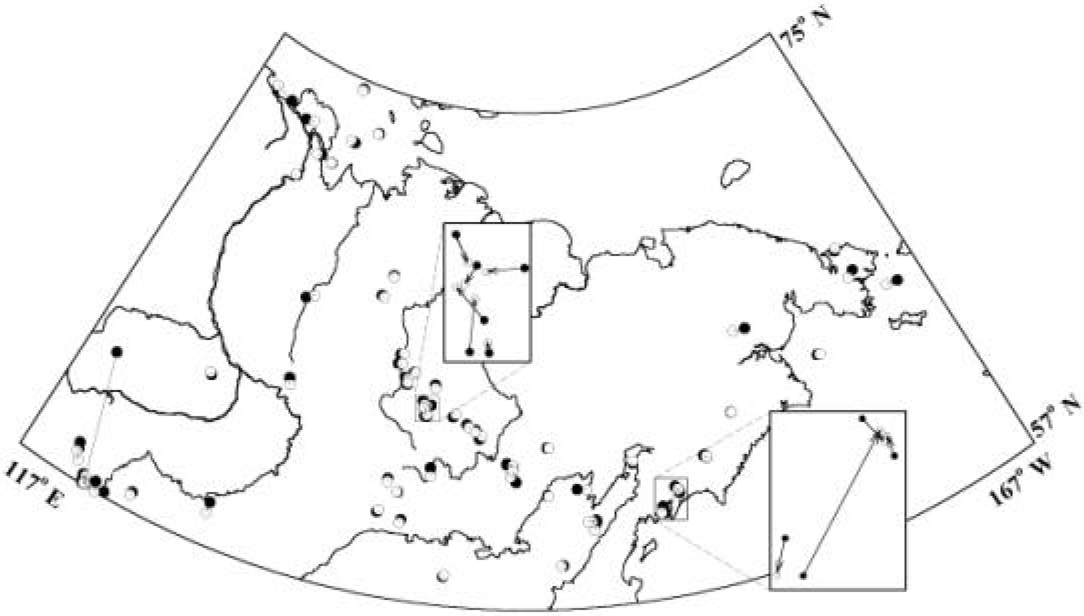

Figure 6. Comparison of ISC epicenters (solid) and relocated epicenters (open) using local data for the northern portion of the study area. Connecting lines show magnitude of displacement. Note that relocations cluster better than ISC determined epicenters (insets).

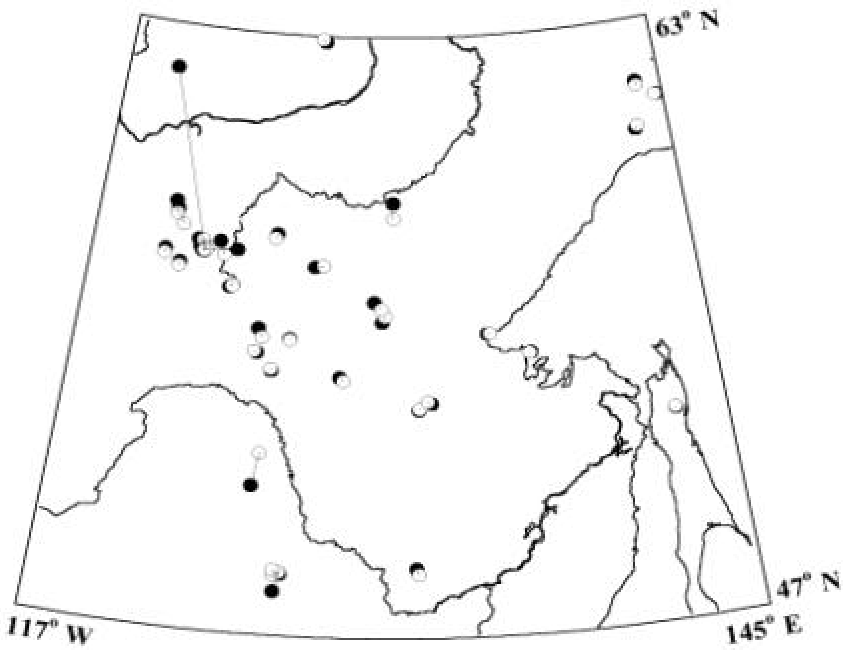

Figure 7. Comparison of ISC (solid) and relocated epicenters (open) using local data for the Amur region. Connecting lines show magnitude of displacement. Note that relocations cluster better than ISC determined epicenters.

Although there are some areas where there appears to be some consistent bias (e.g., the larger events in Chukotka, the Laptev Sea, and also perhaps in the north-central Verkhoyansk Range), the most consistent bias in the in the epicenter shift is "radial" with aftershocks and other events tending to move into tighter clusters (see insets,

Fig. 6). No specific areas stand out as having large differences between ISC and our solutions. Examination of events whose locations have the greatest differences, by more than 45 km, indicate that our relocations are much better than the ISC solutions, with a few exceptions at the edges of our study area.

ISC solutions are generally worse where they have no close stations, or the stations fall into a narrow azimuthal range. Similarly, a few of our solutions at the edges of our study area are worse because we have a narrow azimuthal range, which may also affect our travel-time curve calibrations.

An area where we show clear improvement is Chukotka, where our relocations use both the Russian and American data, hence providing excellent azimuthal coverage. We also locate aftershocks better; generally our solutions fall in closer proximity to the mainshock, as we have larger numbers of close stations. Given the magnitude of even the largest events, M < 7, aftershock areas are not expected to be large. The area where our solutions may have some problems is in the Laptev Sea where, due to our criteria for not using stations greater than 25°, we do not have good azimuthal coverage to the north and the seismic velocities in the crust appear to vary relatively rapidly (Fig. 2).

Based on a preliminary sampling of events we believe that our solutions are better than those reported by the ISC due the increased number of close-in stations, the relatively good azimuthal distribution in most of our study area, and the use of calibrated travel-time curves. We feel that many events meet GT10 criteria, and a reasonable number may qualify as GT5. Additional careful analysis of individual solutions may lead to further improvements in our ability to obtain ground-truth values.

Regional network deployment

In the summer of 1999, we began a program to develop seismic discriminants for CTBT monitoring by converting existing photopaper analog stations in the Magadan and Yakutsk networks to digital data acquisition. At present, we have deployed seven stations in northeast Russia, most in the Magadan region (Figure 8). All stations are 3 component, with three stations recording broadband instruments (Seymchan - STS-1, Okhotsk - Guralp CMG-40T, and Anadyr - 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 photopaper stations.

Figure 8. Map of the Magadan region showing locations of digital seismic stations deployed in 1999 and 2000 (closed triangles). Also shown are supporting analog stations (open triangles) and future mine deployment sites (circles).

We are presently beginning the process of identifying and analyzing the local earthquakes and explosions in the digital data. Two of our stations are located in active mining regions, which supports acquisition of ground truth data directly useful for calibration of the IMS Alternate stations Magadan (MA2) and Seymchan (SEY).

Figure 9 shows a mine blast near Susuman, which was recorded at Seymchan, Magadan and other regional stations. Figure 10 is a sample record of a local earthquake. In addition to locally occurring events, several hundred regional and teleseismic events have also been recorded at the deployed stations.

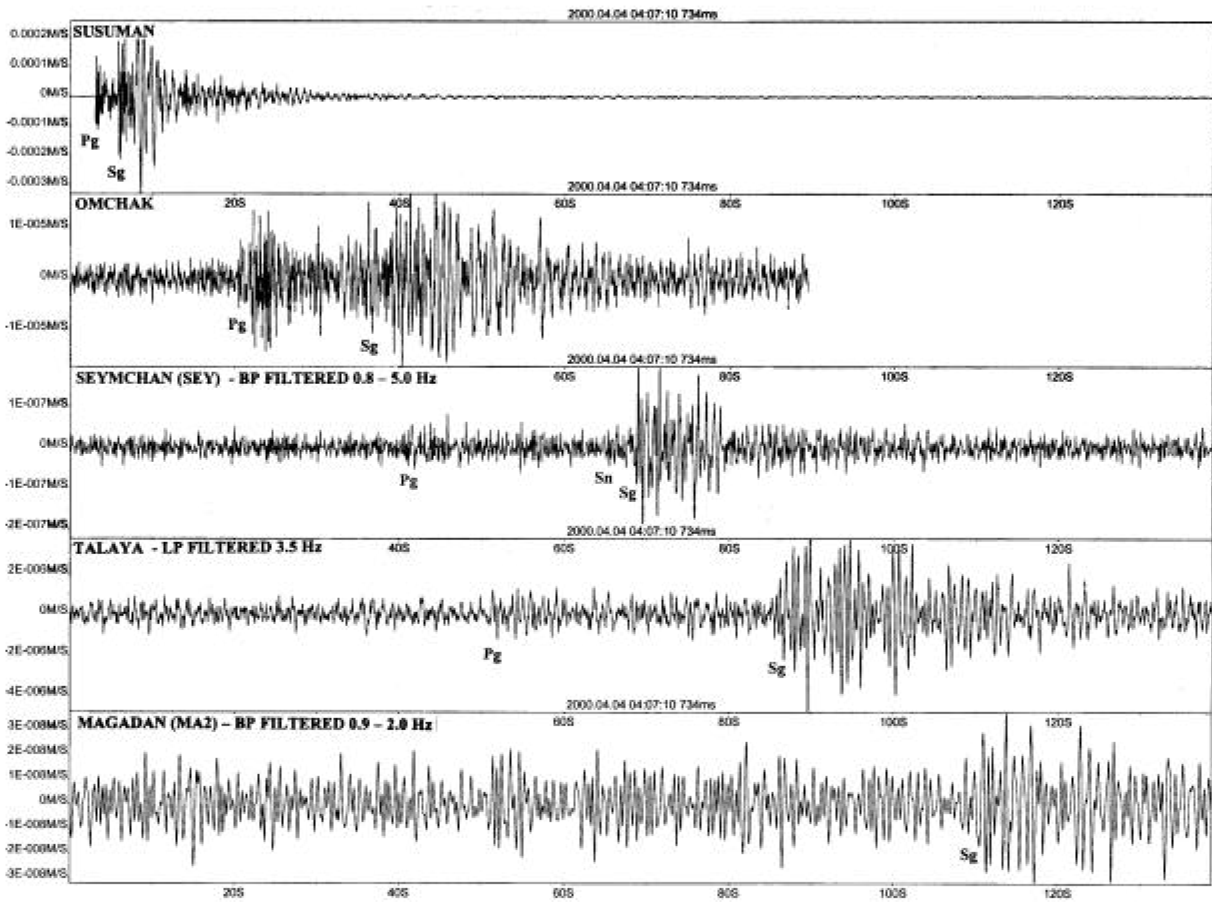

Figure 9. Sample seismograms from an April 4, 2000 mine blast as recorded by five stations in northeast Russia. The blast occurred approximately 25 km northeast of Susuman, and was recorded at the IMS alternate stations Seymchan (SEY; see middle trace) and Magadan (MA2; see lower trace).

CONCLUSIONS

By determining locally calibrated travel-time curves and relocating regional earthquakes recorded by regional networks operating in northeast Russia, we have greatly improved epicenters relative to both the original Russian determination and the ISC Bulletin. Nominal errors are less than 10 km and, with most events having good azimuthal coverage and several stations within several hundred kilometers reporting both P and S arrivals, many of these events may meet GT5 criteria. In order to improve our ability to obtain ground truth events, we have deployed a network of digital stations in the Magadan District, including at or near mines. The data from this deployment is currently under analysis.

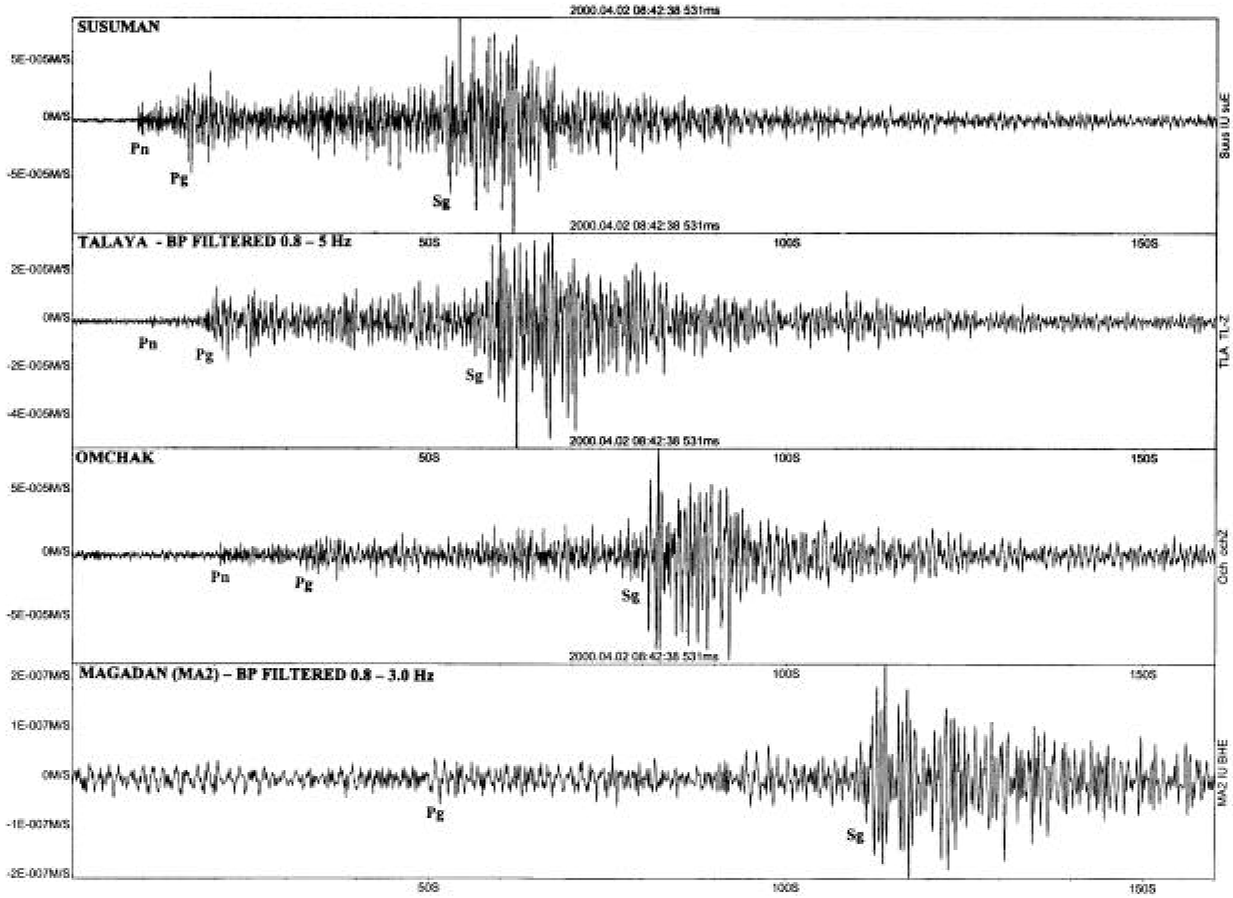

Figure 10. Sample seismograms depicting a local earthquake as recorded by stations of our network in northeast Russia. This event occurred on April 02, 2000, at approximately 63.9°N x 154.1°E.

REFERENCES

Drachev, S., Savostin, L. A., Groshev, V. G., and Bruni, I. E., 1998, Structure and geology of the continental shelf of the Laptev Sea, Eastern Russian Arctic: *Tectonophysics*, v. 298, p. 357-393.

Fujita, K., Cambray, F.W., and Velbel, M.A., 1990, Tectonics of the Laptev Sea and Moma rift systems, northeast USSR: *Marine Geology*, v. 93, p. 95-118.

Jeffreys, H., and Bullen, K.E., 1970, *Seismological Tables*: Office of the British Association, London, 50 pp.

Kennett, B.N.L., 1991, *IASPEI 1991 Seismological Talbes*: Research School of Earth Sciences, Australian National University, Canberra, 167 pp.

Kogan, M. L., 1974, Conducting seismic work of the CMRW-DSS on oceanic ice on the shelves of the Arctic seas (example of work in the Laptev Sea): *Geofizicheskie Metody Razvedki v Arktiki*, vyp. 9, p. 33-38.

Mackey, K.G., and Fujita, K., 1999, The northeast Russia seismicity database and explosion contamination of the Russian earthquake catalog: in *Proceedings of the 21st Seismic Research Symposium: Technologies for Monitoring The Comprehensive Nuclear-Test-Ban Treaty, 21-24 September, 1999, Las Vegas, Nevada*, v. 1, p. 151-161.

Mackey, K.G., Fujita, K., and Ruff, L.J., 1998, Crustal thickness of northeast Russia: *Tectonophysics*, v. 284, p. 283-297.

Nokleberg, W.L., Parfenov, L.M., Monger, J.W.H., Baranov, B.V., Byalobzhesky, S.G., Bunbtzen, T.K., Feeney, T.D., Fujita, K., Gordey, S.P., Grantz, A., Khanchuk, A.I., Natal'in, B.A., Natapov, L.M., Norton, I.O., Patton, W.W., Jr., Plafker, G., Scholl, D.W., Sokolov, S.D., Sosunov, G.M., Stone, D.B., Tabor, R.W., Tsukanov, N.V., Vallier, T.L., Wakita, K., 1994, *Circum-North Pacific tectonostratigraphic terrane map*: U. S. Geological Survey Open-File Report 94-714, 221 pp., 5 plates.

Suvorov, V.D., and Kornilova, Z.A., 1985, Deep structure of the Aldan shield according to near earthquake data: *Soviet Geology and Geophysics*, v. 26 (2), p. 79-84.

Suvorov, V.D., Parasotka, B.S., and Chernyi, S.D., 1999, Deep seismic sounding studies in Yakutia: *Izvestia, Physics of the Solid Earth*, v. 35 (7-8), p. 612-629.