SEISMIC REGIONALIZATION RESEARCH IN NORTHEAST RUSSIA

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ABSTRACT

In an effort to characterize seismicity in support of nuclear explosion monitoring for the continental regions of northeast Russia, we have continued field deployments in eastern Russia to acquire seismic ground-truth and waveform data. Recent fieldwork includes a ground-truth derived travel-time curve in the central Magadan region, as well as a seismic aftershock study in eastern Chukotka. We also continue to develop and make use of an extensive database of historic seismic bulletins covering all of northeastern Russia. To this end, we have parsed and merged six separate Siberian bulletins into standard database tables and from those tables produced a comprehensive map of Siberian seismicity covering the years 1960 to 2003.

We conducted an experiment in the Susuman gold mining region in northeastern Russia where many large explosions occur each spring. In this study, we used five explosions having ground-truth origin times and locations (+/- 150 m), and nine temporary seismic station deployment sites to construct a general travel-time curve for the region extending east from Susuman to the seismic station at Seymchan, a maximum distance of approximately 240 km. Using these ground-truth explosions, we determined that along this profile Pg velocity is 5.96 km/s and Sg velocity is 3.51 km/s. Additional phase arrivals are also noted which may correspond to PmP, P*, and/or other phases, although Pn and Sn arrivals are not clearly visible. A qualitative analysis of data recorded at Seymchan show that high noise levels obscure the majority of events that are clearly recorded at sites only a few kilometers out of town. This applies to the Susuman explosions we recorded, which are not visible in the Seymchan Station data without filtering, while they are clear at nearby but remote sites. This is important to note because the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) will soon open Seymchan as an International Monitoring System (IMS) auxiliary station.

In December 2002 a magnitude 4.2 earthquake occurred in eastern Chukotka. This began an extensive aftershock sequence/seismic swarm of small but felt events that continue to the present (June 2004). In September 2003, we deployed one permanent and two temporary seismic stations in and around the village of Neshkan. As a result of events located in this deployment, we were able to determine a fault trace that runs essentially under the town. With the use of additional data from western Alaska, we find that teleseismically recorded events located in this area are likely to have calculated epicenters approximately 5–10 km too far west.

Our bulletin parsing and merging efforts have produced database tables holding information from about 210,000 event locations ranging from around 105 degrees east longitude to across the Bering Strait into western Alaska. Also included are locations from Sakhalin Island and the Kamchatka Peninsula. We hold arrival times for about 80,000 of these events. The original sources for this information varies from published, Siberia-wide Russian earthquake bulletins to unpublished bulletins of regional network operators. We are currently working on a new-site table of consistent station names and locations, and we are parsing pre-1960 historic bulletins and mining explosion catalogs, with plans to insert this information into our Siberia database.

OBJECTIVE

The objective of our research is to improve event location and identification capability in eastern Russia in support of nuclear explosion monitoring.

RESEARCH ACCOMPLISHED

Ground Truth Velocities in the Susuman Region

The Susuman region in Northeastern Russia is an active gold mining region in which many large explosions occur each spring. In April 2004, we recorded five mine explosions (three from Kholodnie mine, two from Teekhee mine) ranging in size from 45 to 72 tons to construct a seismic profile. Ground truth origin times and locations (+/- 150 m) were obtained for all explosions by deploying a seismic station at the mine. These explosions were used to construct a general travel-time curve for the region extending east from Susuman to the seismic station at Seymchan, a maximum distance of approximately 240 km (Figures 1 and 2A). For each explosion, two field stations were deployed, and moved progressively farther along the profile prior to the next blast. In total, nine temporary seismic stations were deployed between Susuman and Seymchan. Each deployed station was 3-component, using SM3 seismometers, and was digitally recorded at 100 sps on a 24 bit A/D with a GPS clock. As this work was conducted in late winter in a remote region, all stations were deployed via snowmobile. We found that the most practical place for station deployment to be on small frozen streams (Figure 2B). As the region is generally permafrost, small streams are frozen solid completely through and thus provide a ready-made hard flat surface. Bedrock outcroppings were essentially impossible to find given the snow cover.

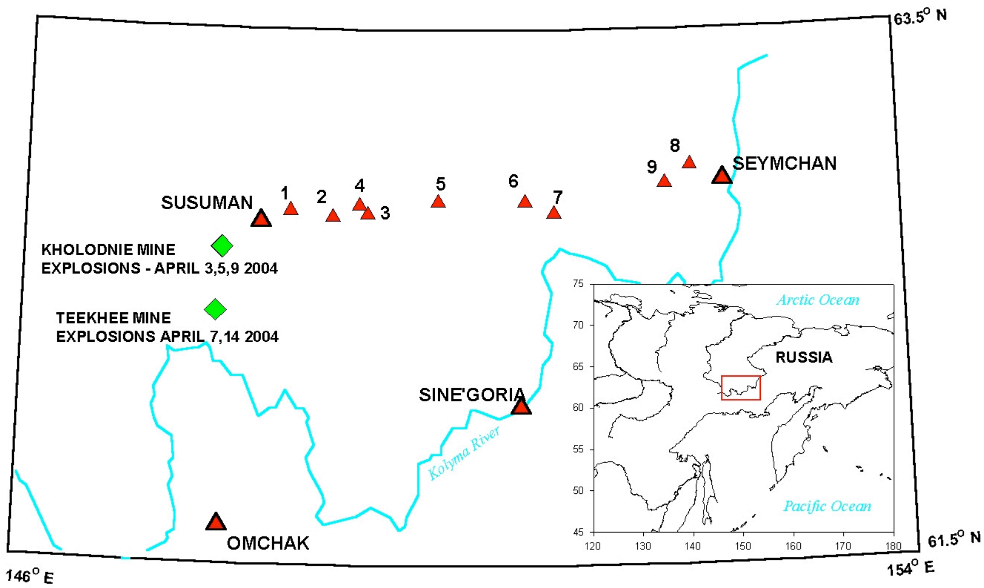


Figure 1. Seismic stations (numbered) deployed between seismic stations at Susuman and Seymchan for a seismic profile to determination ground-truth velocities in the region. Explosions originated from the Kholodnie and Teekhee mines. Other permanent regional seismic stations are also shown. Additional stations off the map also recorded some of the explosions.

In addition to stations directly along the profile route, other permanent seismic stations also recorded the explosions, contributing arrivals at distances up to 470km. Using these ground-truth explosions, we observed that the crustal seismic velocities increase slightly with distance. Velocities at about 25 km from the source are 5.798 km/s for Pg, and 3.490 km/s for Sg. At 230 km, these velocities are increased to 6.113 km/s and 3.5239 km/s for Pg and Sg respectively. Sg velocities to the north of Susuman increase only slightly more to 3.565 km/s at a distance of 470 km. Although Pg and Sg arrivals are clearly observed out to several hundred kilometers, Pn and Sn arrivals were not clearly observed at any distance. The Pg and Sg velocities determined are very close to the crustal velocity model developed by Mackey *et al*., 2003a, where velocities for this region were found to be 6.025–6.075 km/s for Pg and

3.51–3.53 km/s for Sg. The close match of the ground truth velocities imparts a strong degree of validation to the crustal model. Sample explosion seismograms at varying distances recorded during this fieldwork are shown in Figure 4.

a.

b.

Figure 2. 2.a. 47,775 kg explosion at the Teekhee placer gold mine on April 14, 2004. 2.b. typical station setup used for temporary stations deployed along the profile. The SM3 short period sensors are sitting on a small frozen stream, which was determined to be the best deployment option given field conditions and logistics. The small streams are completely solid, thus there is no hydroacoustic noise produced. As the streams are very shallow (5–20 cm) there are no problems with acoustic impedance between the ice and underlying rock. This is Station Site #2 in Figure 1.

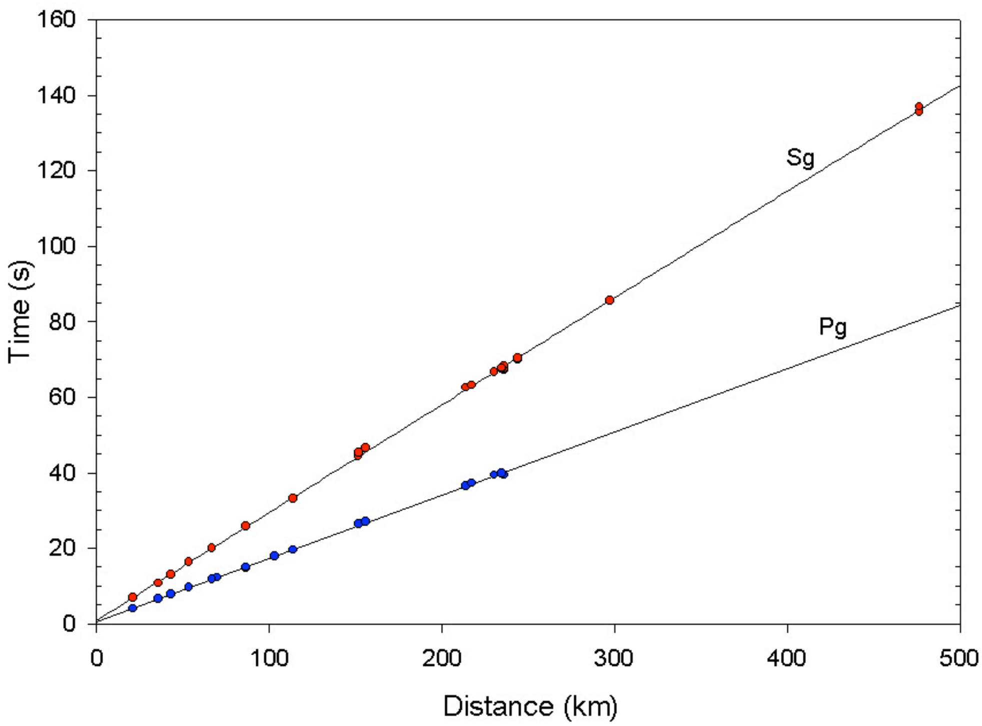


Figure 3. Ground-truth crustal travel-time curve derived from mine explosions. There were no Pn or Sn arrivals that were sufficiently clear to pick times with any degree of confidence. Data points are fit with a second-order regression curve.

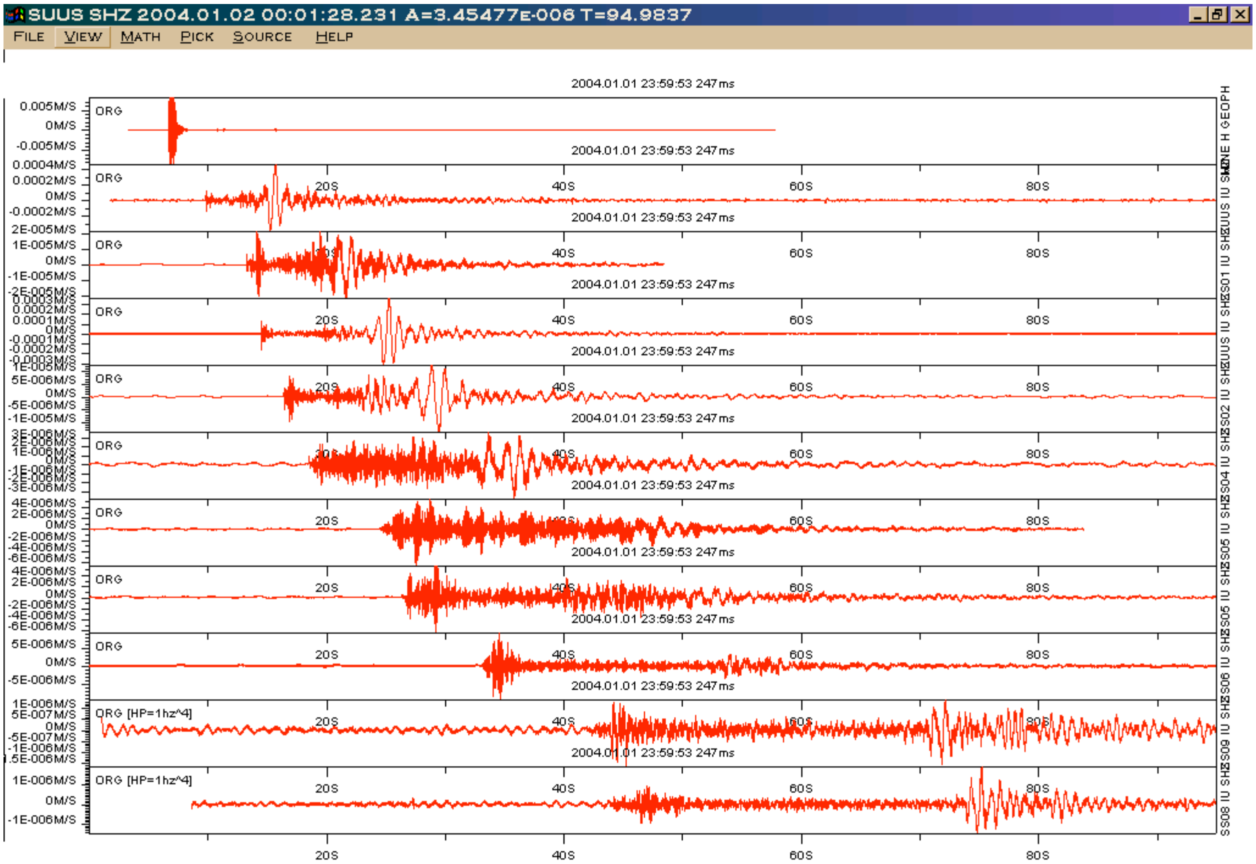


Figure 4. Sample explosion seismograms of mine explosions used to derive ground truth velocities. These records vary in distance from 0-230 km. All traces are unfiltered except the bottom two traces, to which a 1-Hz-high pass filter was applied.

Quality of Future CBTBO Recordings at Seymchan

A qualitative analysis of data recorded at Seymchan shows that high noise levels obscure the majority of events that are clearly recorded at sites only a few kilometers out of town. For instance, the Susuman explosions recorded here, are not visible in the Seymchan Station data without filtering, while they are clear at nearby but remote sites. The situation is easily illustrated by comparing seismograms from the April 14 explosion as recorded at Station 8 and Seymchan (Figures 1 and 5). In this case raw, unfiltered data from Station 8 shows a clear seismogram with a lot of information, while the same raw, unfiltered data from Seymchan does not show any obvious event. It is possible to see the event at Seymchan by filtering the data in a narrow frequency range, though it is not possible to obtain a clear seismogram (Figure 5). Horizontal components of Seymchan are even noisier than the vertical component shown. In comparing these seismograms it is important to note the differences in both stations. Station 8 used short period SM3 seismometers, while Seymchan records STS-1 Streckheisen seismometers. Station 8 was a hastily prepared site on a frozen stream and not thermally isolated, while the sensors at Seymchan are situated on a buried concrete pier in a thermally controlled underground vault. For this explosion, Station 8 was 13 km closer to the explosion (230 km) than Seymchan (243 km). A similar recording situation exists for earthquakes. Station 8 operated continuously for four days and recorded over 50 local and near-regional earthquakes. Of those events, only a few are visible at Seymchan. The problem in Seymchan is that the station is situated only one block from the center of the town, and more importantly, a coal fired heating plant is situated about 100 m from the station. The heating plant operates grinders for processing coal, which produces a large amount of anthropogenic noise on the seismograms. The situation is somewhat better during the summer months (mid May to mid September) when the heating plant is not in operation. This discussion on Seymchan is important to note because CTBTO will soon open Seymchan as an IMS auxiliary station. The CTBTO instruments will reside in the same seismic vault as the current STS-1 instruments shown here, and thus subject to the same levels of anthropogenic noise.

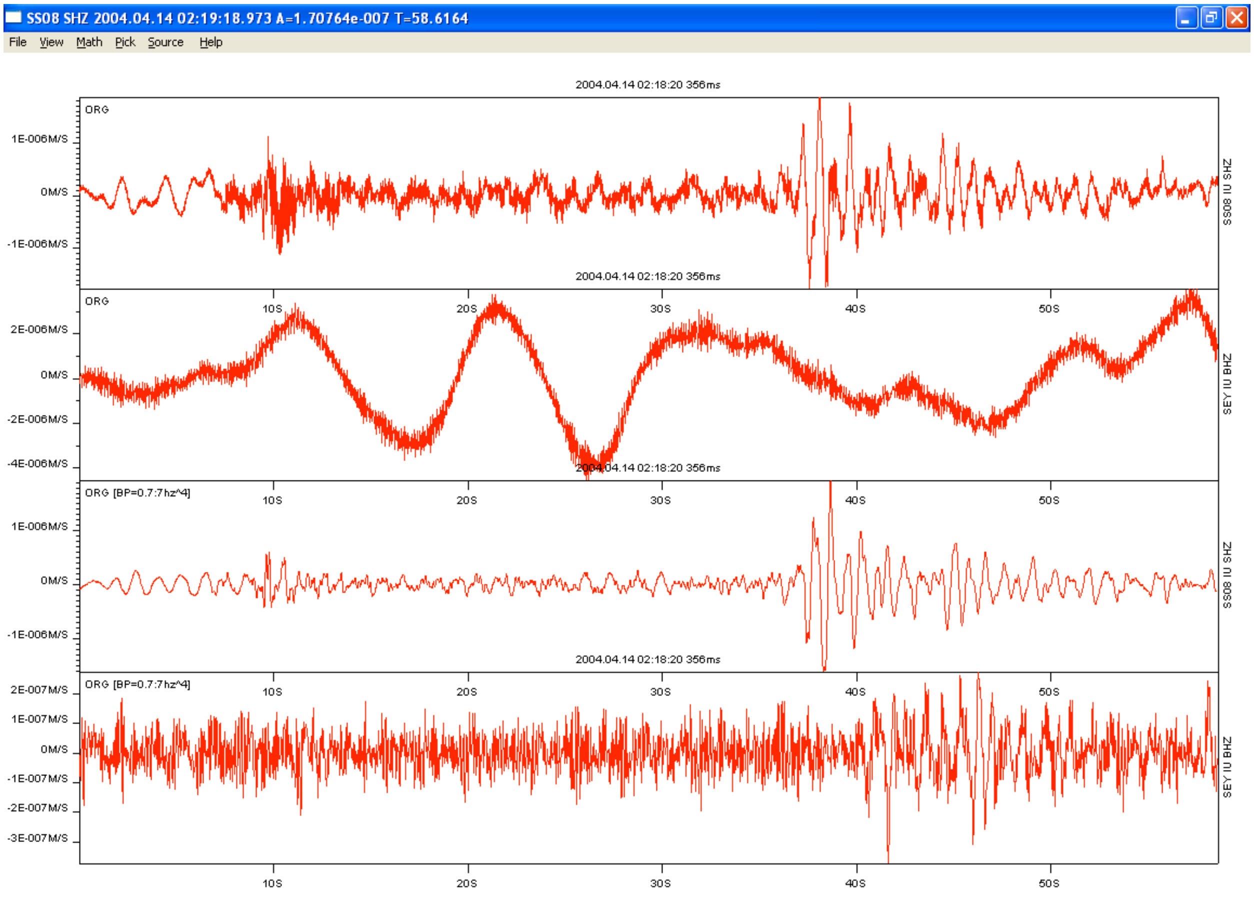


Figure 5. Seismograms from the 47,775 kg April 14, 2004 mine explosion. The top trace is unfiltered data from Station 8 (230 km distant), while the second unfiltered trace was recorded at Seymchan (243 km distant). The bottom two traces are the same data bandpass filtered from 0.7–7 Hz.

Neshkan Aftershock Study

The village of Neshkan, located along the Arctic coast of Chukotka in northeastern Russia, has been experiencing felt earthquakes almost daily since a M_L 4.2 (4.1 m_b) earthquake occurred on December 9, 2002 (Figure 6). The mainshock and several aftershocks over several months were large enough to be included in the Reviewed Event Bulletin (REB). The continuing aftershock sequence allowed us to deploy temporary stations in the region and determine the extent of the aftershock zone, and compare it with teleseismically determined hypocenters.

The tectonic setting of the area is poorly understood, but recent cooperative work with our Russian colleagues, combining teleseismic and regional seismic data, have suggested that the area is in an extensional setting, which is contiguous with rift systems proposed in Seward Peninsula, Alaska (Mackey *et al*., 1997; Fujita et al., 2002).

For the 2003 Neshkan experiment, three seismic stations were deployed. The main station, Neshkan (NSH), is a three component short period station deployed in the village of Neshkan. Two temporary stations were also deployed in the tundra (Table 1). Both temporary stations were single-component using a short period vertical seismometer. Station NSH1 failed shortly after installation due to an instrument problem.

Over approximately 18 days of operation, the Neshkan temporary deployment recorded approximately 150 earthquakes, most at Station NSH. The largest event recorded during the experiment had a K-class of 9.4, which corresponds approximately to M_L 3.4. Most events recorded were considerably smaller. Only events with clear Pg and Sg arrivals recorded at both operating stations were located. For these locations, first motions at the three component Station NSH were determined to constrain the approximate location of the source. Considering that the closest events have an S-P time of only 0.6 seconds, we obtain a maximum possible depth for many events near Neshkan of only 5 – 7 km, assuming the event is directly below the station. By assuming a shallow hypocenter depth (5 km), an approximate epicenter based on first motion polarities, and using Pg and Sg times from both stations, we are able to locate the earthquakes. A sample seismogram is shown in Figure 7.

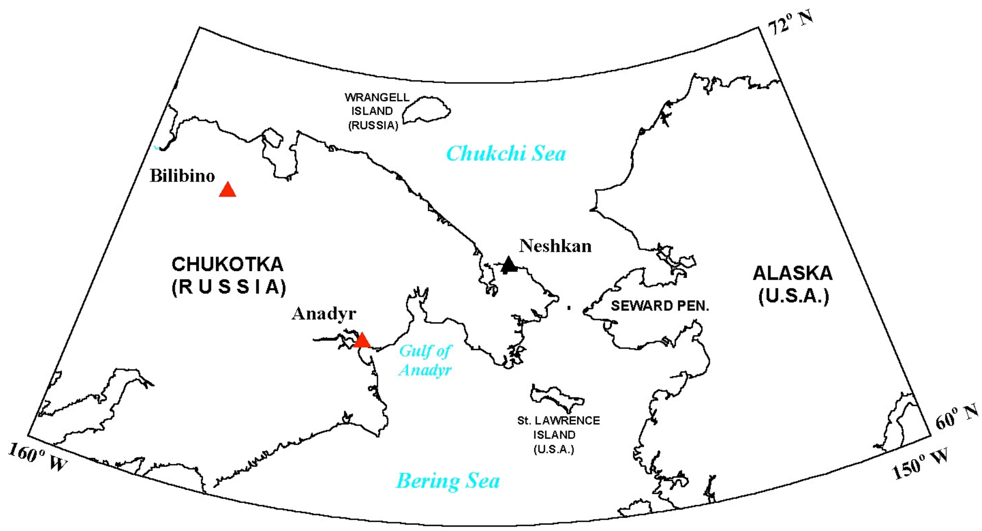


Figure 6. Neshkan is located on the north coast of Chukotka, near the Bering Strait Red triangles indicate the open seismic stations in Chukotka during the first nine months of the aftershock sequence.

Results from 18 locatable events fall in a linear zone extending from Neshkan to approximately 20 km to the south-southwest (Figure 8). We suggest that this linear trend of earthquakes represents a specific but previously unknown active fault in close proximity to the village. Located epicenters indicate that this fault may be within 1 km of the town, to the west. In addition, a small pond located approximately 1 km west of the village had drained for the first time in people's memory by spring, 2003, suggesting that there may have been some surface deformation over the course of the earthquake sequence. Approximately 500 m west of the village, there is an extensive region of rapidly eroding permafrost sand deposits. The erosion is facilitated by extensive cracks in the permafrost, allowing water to penetrate and melt the permafrost in the warmer summer months, causing the crack to expand as material is washed out. It is the recollection of the village administrator that the cracks may have first appeared in 1997. This would be consistent with a small amount of surface deformation resulting from the Magnitude 6.0 Neshkan earthquake in October 1996. It should be noted that the exact date or year this erosion began might not be recalled exactly correctly. No other similar fractured erosional areas were observed in approximately 15 km of walking along the beach to the west of Neshkan.

Following the end of active fieldwork in the Neshkan region, the main seismic station (NSH), was left in place as a permanent station site. Analysis of data from September 12 through early 2004 show over 1500 earthquakes recorded, with the sequence still active as of June, 2004.

Table 1. Seismic station parameters

Station	Latitude	Longitude	Elevation (m)	Date Open — Close
NSH	67.036	-172.960	5	12/9/2003 –
NSH1	66.263	-173.328	29	Did Not Operate
NSH2	67.107	-173.635	65	12/9/2003–30/9/2003

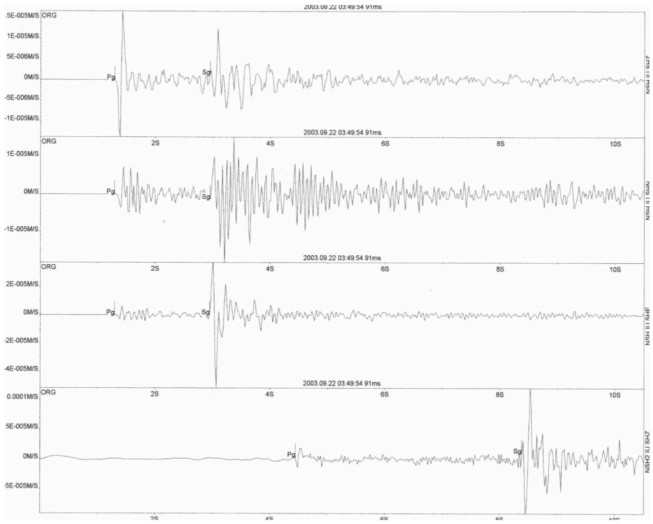


Figure 7. Event with dilatational arrivals at Station NSH. Components are, top to bottom, Z, N-S, and E-W. The bottom trace is the vertical from Station NSH2.

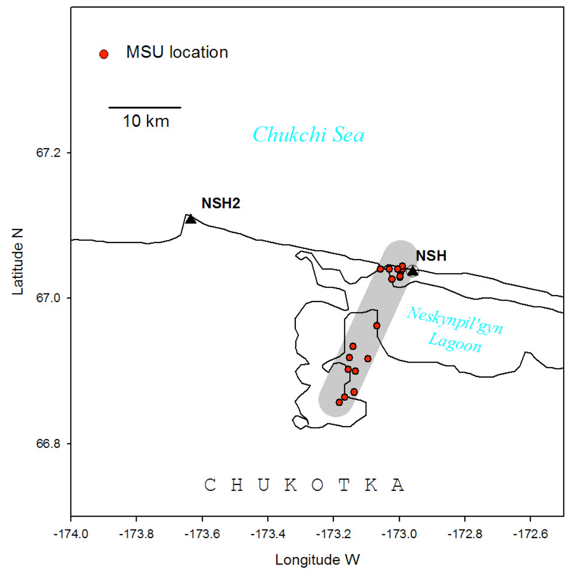


Figure 8. Earthquakes located near Neshkan from our deployment in September 2003.

Location Quality of Recent Teleseismically Recorded Events

We can compare the seismic trend defined from the recently located events of this study to earlier teleseismically located events. The most recent large earthquake near Neshkan was the magnitude 6.0 Chukotka event of 1996, which was followed by an aftershock sequence (Figure 9). Several of the aftershocks ranging is size from magnitude 3.0–5.0 were also recorded and located teleseismically. There are no locations or data on small events in the aftershock sequence as there were no local stations. The mainshock from this sequence is teleseismically located approximately 5 km west of the center portion of the trend defined in this study. The larger aftershocks are generally within 10 km, while smaller aftershocks are located up to 30 km from our currently observed trend. Considering the proximity of the 1996 mainshock, distribution of aftershocks, and realistic epicentral errors, we suggest that the 1996 sequence occurred on the same fault segment. Unfortunately, it is not currently possible to greatly improve the locations of these teleseismic events as no local data are available.

The current swarm of earthquakes near Neshkan began with a M_L 4.2 on 9 December 2002. Other magnitude estimates for this event range from 3.9–4.7, depending on magnitude type and source. Several teleseismically recorded aftershocks also occurred, primarily reported in the REB. The REB teleseismically determined mainshock epicenter appears to be mislocated approximately 10 km too far west, similar to events of the 1996 sequence, relative to our newly defined trend. Through October 2003 the REB reports six additional events, having magnitudes between 3 and 4, which may be aftershocks occurring in this sequence (There is also one possible foreshock on 22 June, 2002; See below). The REB locations for these events vary considerably, thus it is not initially clear which of them are actually associated with mainshock (Figure 10.a.). Of the six possible aftershocks, 5 were felt strongly in Neshkan (Mackey *et al*., 2003b). For the events reported in the REB, we obtained additional seismograms from four stations operated by the Alaska Earthquake Information Center (AEIC). Arrival times at the Alaska stations were used in conjunction with teleseismically reported arrivals to relocate the events. The relocations were computed using calibrated Pg and Sg velocities for the region using the model and methodology as described in Mackey (1999) and Mackey *et al*. (2003a).

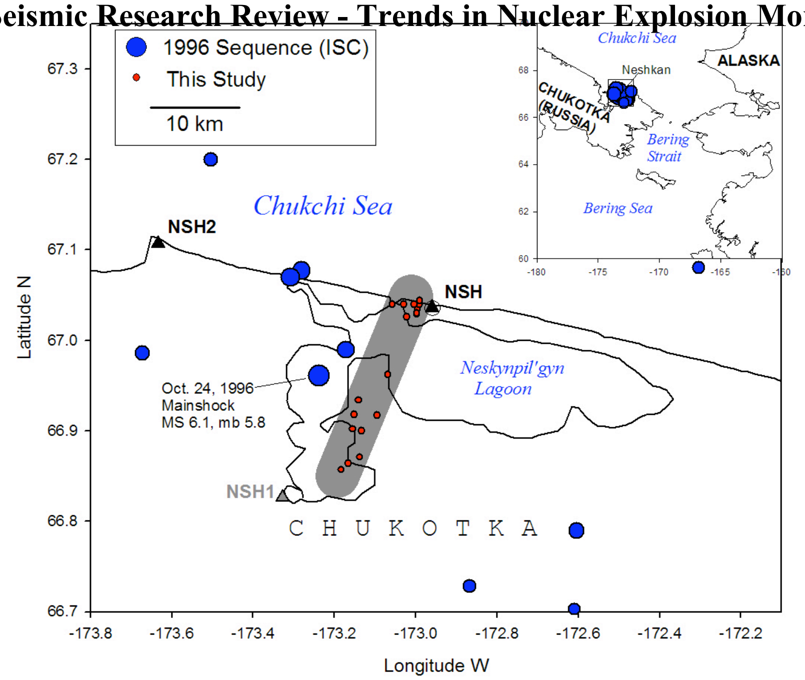
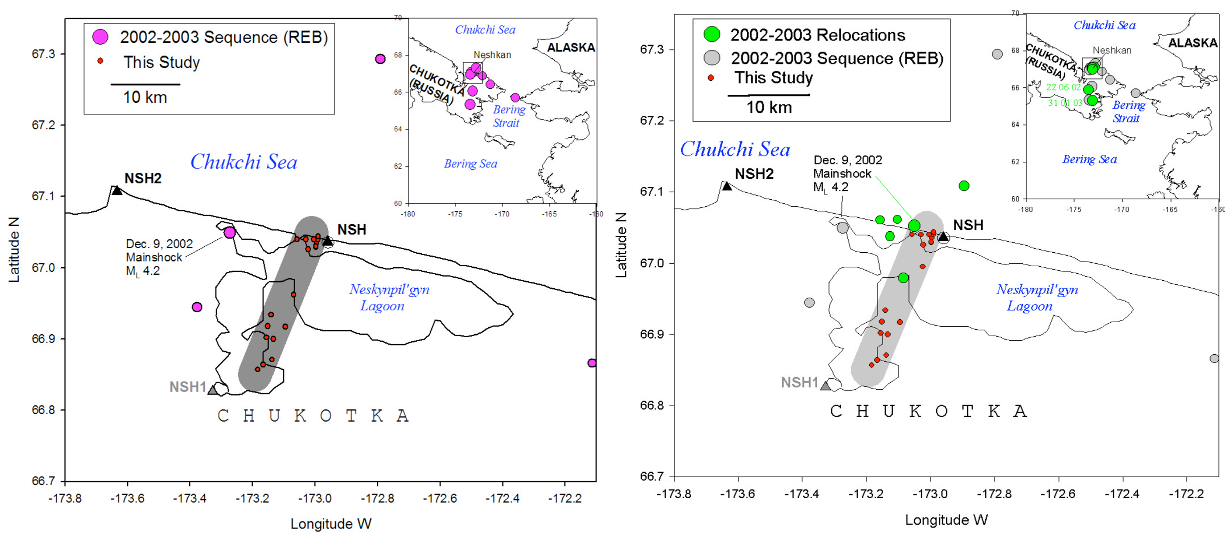


Figure 9. Comparison of teleseismic locations of the 24 October 1996 earthquake and associated aftershocks to the currently active aftershock zone. The 1996 sequence may fall on the same fault segment, with location differences being due to epicenter calculation errors. In general, the larger event teleseismic locations appear to be 5–10 km systematically to the west of our aftershock zone



a **b**

Figure 10.a. Comparison of REB determined epicenters to the aftershock zone determined here. Note that several events are only located on the map inset, while the mainshock locates west of our defined trend. Figure 10b. Relocations of the REB reported events, using supplemental arrivals from Alaska stations and using the crustal velocity model of Mackey *et al*., 2003a. The relocated mainshock plots within the aftershock zone and other aftershocks cluster close. Two other events reported in the REB locate far to the south of, which also consistent with felt reports from Neshkan.

Relocation of the 9 December 2002 mainshock moved the epicenter approximately 10 km east, placing it on the west edge of the northern, and most active, portion of our defined trend (Figure 10b). All other REB-reported epicenters following the 9 December 2002 event except one are also found to cluster on or near our fault trend. The 31 January 2003 event reported in the REB was found to locate approximately 150 km south of Neshkan. Of the possible REB-reported aftershocks, this was also the only earthquake not reported as felt in Neshkan. Another event, occurring on

22 June 2002, was evaluated to see if it might have been a foreshock of the Neshkan events. Relocation of this event using Alaska data shows this event also to be located approximately 100 km south of Neshkan. Both of the non-Neshkan events are associated with other trends in the historic seismicity. Overall, the relocations are a significant improvement over the REB-determined epicenters, with two events moving more than 100 km. In the relocation process, depths were allowed to vary freely. The depths for all events converged between 2 and 16 km. Showing conclusively that the mainshock, and five of the six possible REB aftershocks, are associated with the northern end of the defined trend allows us to use, with a reasonable degree of certainty, these events to improve future teleseismic locations in the region by providing travel-time residuals and source specific station corrections (SSSC's) for eastern Chukotka. Unfortunately the events were not large enough to provide useful corrections to many teleseismically-reporting stations. It may be possible to obtain reasonable SSSC's for several of the seismic arrays that may have recorded the events. The events will also be useful to improve locations of future events in the area with the available local and near regional stations. In conclusion of the Neshkan study, teleseismic locations (REB, ISC) of moderate- to well recorded events in this area appear to be mislocated 5−10 km west of the true epicenters. Based on the relocated teleseismic events association with the determined aftershock region, the location methodology and crustal-seismic velocities in Mackey *et al*., 2003a appear to be valid for the region.

Database Improvements

Michigan State University (MSU) has accumulated a large volume of catalog and bulletin information (both electronic and paper) from several Russian sources. One of our main efforts has been to merge all of this information into one common source. To accomplish this, we have parsed, merged, and inserted many catalogs and bulletins into SQL-style database tables following the NNSA schema. The database consists of event, origin, origerr, arrival, assoc, amplitude, stamag, netmag, remark, and site tables. Many data files provided by MSU covered specific network bulletins and catalogs and other files had already been merged by MSU into Siberia-wide bulletins. Initially, each file was parsed and inserted into an appropriate, individual suite of database tables keyed to network. Table suites included data from (1) Kamchatka, (2) Irkutsk, (3), Sakhalin, (4) merged bulletins (primarily from Magadan and Yakutsk), and (5) region-wide catalogs from other Russian sources. Once all data files were parsed and inserted into database tables, we merged origins from the five suites of tables into a final set of tables. We refer to these final tables as the "Siberia database." We merged events by ranking origin authors and defining maximum-allowable time and distance separations between origins based on origin author. In total, 66 origin authors were used to insert 209,982 events into the Siberia database. About 72,000 of these events have additional origins reported by more than one source.

The Siberia database spans from pre-instrument times (1725 to the early 1900's) to sparse-instrument times (1900 to 1960) and on through the era of analog, and then digital, regional instruments to 2003. We hold over 1.31 million arrival times and 590,000 amplitude measurements beginning in 1970, and ranging up through the present. Many of these amplitudes contributed to Russian "k-class" event-size estimates, and nearly all events have a k-class measure stored in our netmag table. We have also accumulated information on over 11,000 industrial explosions from throughout the Magadan region (1977 to 2003). The catalog lists the approximate parameters of the explosions. Arrival times from Magadan network stations are included for explosions occurring in 2002 and 2003.

Summarizing the database work, we have made substantial progress in gathering a complete set of digital Siberian seismic information available to MSU under a single set of well-defined SQL-style database tables. While building the tables we have done quality-control work as the data were inserted, and we have developed tools based on the Perl scripting language and the Perl Database Interface modules (DBI) for adding even more information to the Siberian database in the future. Most importantly, we have now been able to exploit the database for research purposes, the first product of which was to produce the most complete seismicity map of eastern Russia (Figure 11).

CONCLUSIONS

In an effort to improve nuclear explosion monitoring for the continental regions of northeast Russia, we have continued field deployments to acquire seismic ground-truth and waveform data. Recent fieldwork includes a seismic aftershock study in eastern Chukotka and a ground-truth derived travel-time curve in the central Magadan region. We have also continued development of an extensive database of historic seismic bulletins covering all of northeastern Russia from which we produced a comprehensive map of Siberian seismicity covering the years 1960 to 2003.

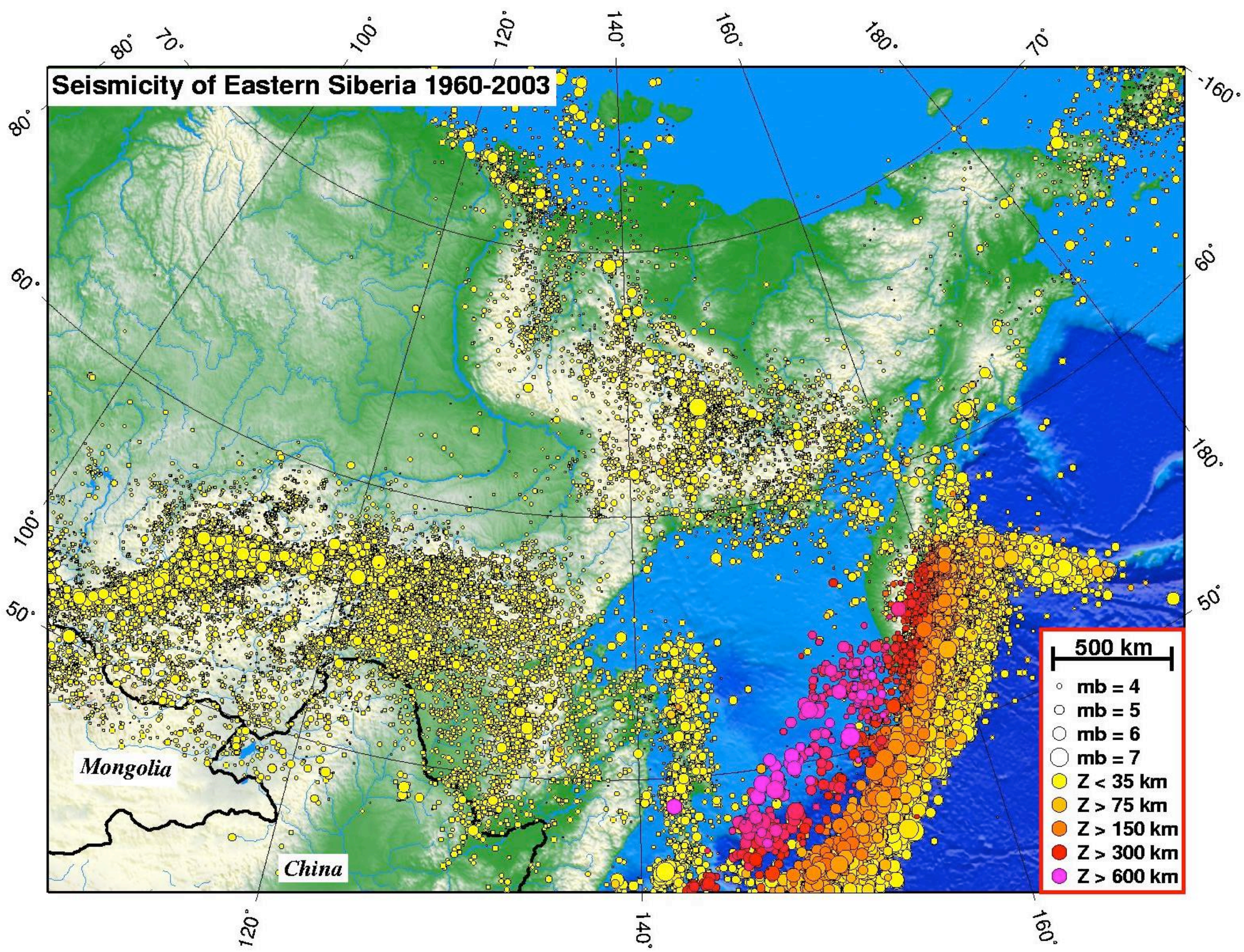


Figure 11. Seismicity map of eastern Russia

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