SEISMIC REGIONALIZATION IN EASTERN RUSSIA

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ABSTRACT

In an effort to characterize seismicity in support of nuclear explosion monitoring for the continental regions of eastern Russia, we have been analyzing information obtained from regional seismic network operators. Our goal is to merge catalog, bulletin, waveform, and other ground truth data from several regional networks into a comprehensive data set that we will use for various seismic research projects. To date we have compiled a bulletin from published and unpublished event data of over 280,000 events, 1,300,000 arrival times, and 580,000 waveform amplitudes. We have also now parsed several regional bulletins into database tables. After parsing into database tables we merged event, arrival, and amplitude information that was originally contained in the different bulletins.

With this merged data set we have been improving and expanding upon crustal velocity models. Preliminary results from the Sakhalin region indicate slow Pg velocities on the order of 5.75 to 5.80 km/s with Sg velocities around 3.35 to 3.37 km/s. We are also estimating velocity models for the Irkutsk region. Crustal velocities in the Irkutsk region are highest in the northwest, with Pg and Sg approaching 6.200 to 6.225 km/s and 3.59 to 3.61 km/s respectively. Velocities in the southeast portion of the Irkutsk region, along the Chinese border, are lower with Pg about 6.05 km/s and Sg around 3.53 km/s. The general velocity gradients observed are consistent with the large-scale regional geology, as well as previously determined velocities for adjacent regions. Our event re-location work to date emphasizes selection of well-recorded events appropriate for estimating source specific station corrections.

We continue deployment of a network of digital stations in northeast Russia to aid in our calibration efforts. We have been obtaining digital waveforms from older stations of this deployment for several years. We have started explosion identification efforts by assembling waveforms based on those explosions that have already been identified by network operators. Using these ground-truth explosion waveforms, we will test discriminants based on body-wave amplitude measurements and cross-correlation analysis, and rank ground-truth events for calibration of far-regional and teleseismic stations.

OBJECTIVES

The objective of our research is to improve event location and identification capability in eastern Russia in support of nuclear explosion monitoring. We plan to reach our objectives through (1) collection, analysis, and merging of historic regional catalogs and bulletins, (2) deployment of additional digital seismic stations in northeast Russia, (3) improving travel-time curves, relocating events, and estimating appropriate correction surfaces for improved locations, and (4) analysis of waveform characteristics to identify effective regional event discriminants.

RESEARCH ACCOMPLISHED

Historic Database for Eastern Russia

Considerable effort has gone into development of a comprehensive historic database for all of eastern Russia. Data sources and the development effort have been previously summarized (Mackey, 1999; Mackey and Fujita, 1999, 2000; Mackey et al., 2002), and a significant amount of new data has been recently added. Our goal is to merge catalog, bulletin, waveform, and other ground-truth data from several regional networks into a comprehensive data set that we will use for various seismic research projects. To date we have compiled a bulletin from published and unpublished event data of over 280,000 events, 1,300,000 arrival times, and 580,000 waveform amplitudes, essentially tripling the amount of data in the past year. We have now parsed over 86,000 events and associated arrival times and waveform amplitudes from several regional bulletins into database tables. After parsing into database tables, we have merged event, arrival, and amplitude information that were originally contained in the different bulletins.

Crustal Velocity Model

A small subset of this database was used to recalculate a crustal velocity model for eastern Russia using a grid search method with a moving window to determine best fit Pg and Sg (Lg onset, but hereafter referred to as Sg) crustal velocities to well located events. The method is the same as that outlined in Mackey (1999) and Mackey and Fujita (2000) except that a moving window of 2.5 x 5° using increments of 0.5°in latitude and 1.0° in longitude was applied to the entire study area to obtain more details on the variation of velocities and avoid artificially sharp discontinuities. Cells calculated using only one event were removed to reduce edge effects. In addition to recalculating velocities for northeast Russia using this improved method, we added the Baikal, Chita, and Sakhalin regions to this analysis using additional phases for Sakhalin, Amur, and the Baikal regions that have recently been added to the database from the "Materials on the Seismicity of Siberia" and the "Seismological Bulletin for the Far East." The model was calculated using 1,708 events that were well recorded by local networks between 1984 and 1996. The results obtained for Pg velocities in northeastern Russia (Figure 1) are generally similar to those discussed in our earlier paper (Mackey and Fujita, 2000); the Siberian platform is generally fast, there are slower velocities along the extension of the Arctic Mid-Ocean Ridge in the southern Laptev Sea and in areas affected by a Pliocene rifting episode, and are average elsewhere. Sg velocities (Figure 2) are also low in regions of rifting, both in and south of the Laptev Sea, as well as along the northern coast of the Sea of Okhotsk where Worrall et al. (1996) have suggested the existence of pull-apart basins as a far-field effect of the India-Eurasia collision. Below, we discuss our new results for southeastern Russia and compare them to velocities obtained from Russian studies.

Velocity Structure of Southeastern Russia

Examination of the results for Pg and Sg show three general velocity regions: 1) very high velocities in the southern Aldan shield; 2) elevated velocities in the Baikal rift and adjacent regions; and 3) very low velocities in Sakhalin. The region has several local travel-time studies and been criss-crossed by a large number of Russian long- and short-range refraction lines, allowing us to compare our results to independently obtained data.

Southern Aldan Shield. Pg velocities of 6.2–6.3 km/sec and Sg velocities of 3.5–3.7 km/sec are observed in the southern Aldan shield. These values are consistent with Pg and Sg values of 6.3 and 3.64 km/sec observed in local surveys in the southern Siberian platform (Suvorov et al., 1999), and the 6.3 km/sec Pg velocity obtained both from PNE-based long-range profiles that sampled the Aldan shield (Egorkin et al., 1987; Pavlenkova and Romanyuk,

1991) and from local earthquake studies (Suvorov and Kornilova, 1985). These high velocities also extend to the coast of the Sea of Okhotsk. All of these results are consistent with a thick, old, Precambrian platform.

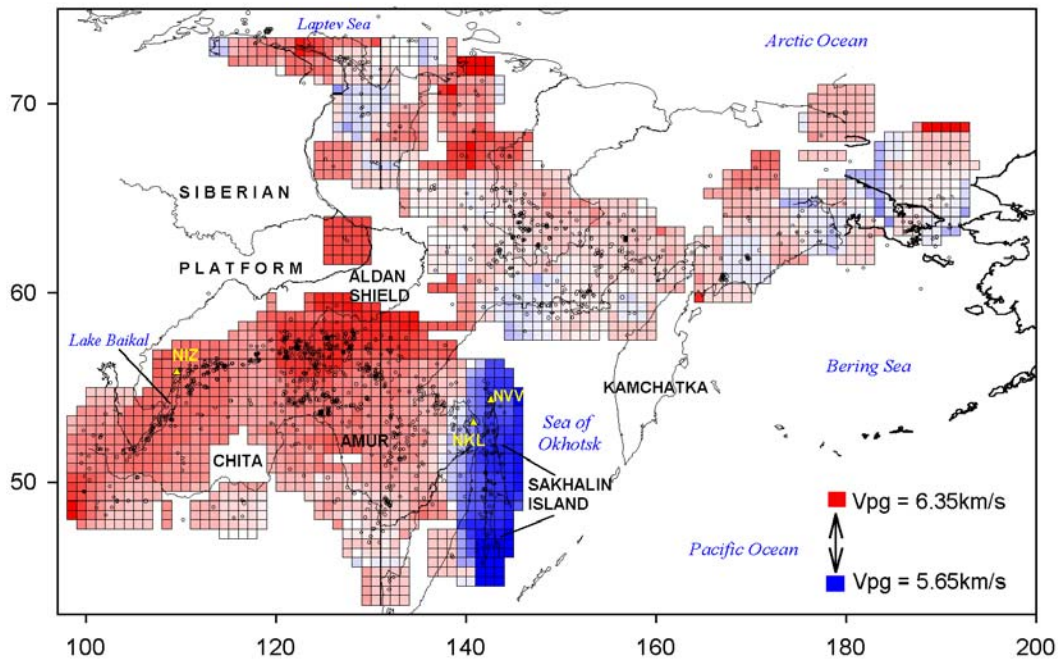

Figure 1. Pg velocity model determined in this study. Events used shown as circles.

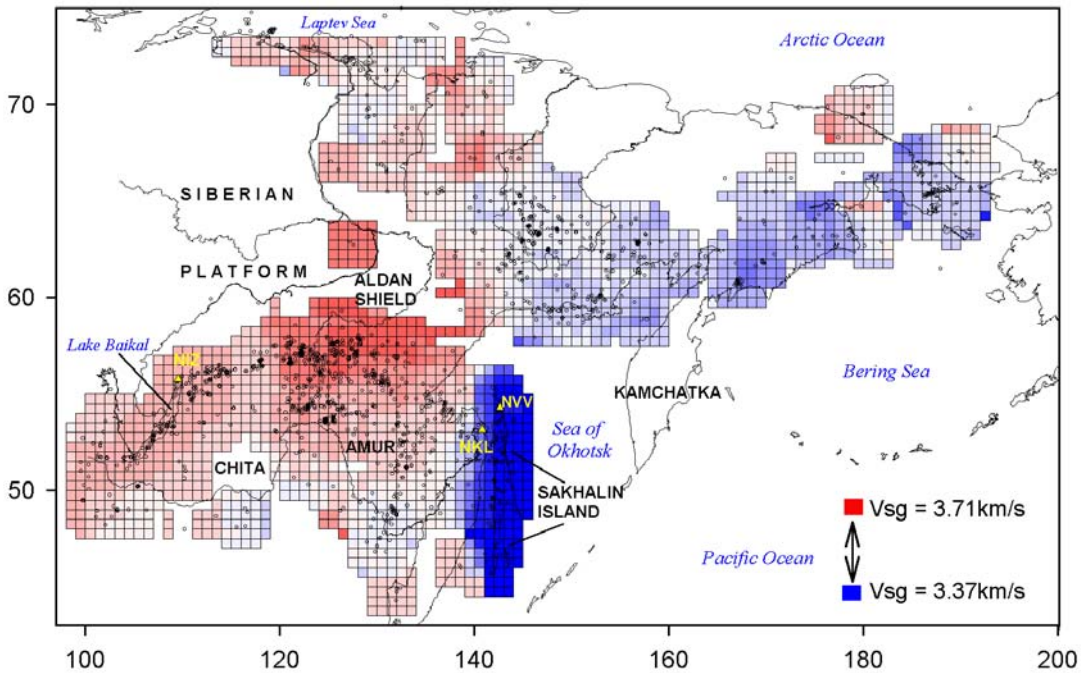

Figure 2. Sg (Lg onset) velocity model determined in this study. Events used shown as circles.

Baikal, Buryatia and Chita Regions. Pg velocities along the Baikal rift zone and to the southwest, towards Lake Khosgobul, are about 6.2 km/sec. In the northeastern extension of the Baikal rift, in the Upper Angara, Muya-Kaunda, and Chara basins, velocities are slightly lower, 6.10–6.15 km/sec. To the southeast of Baikal, in eastern Buryatia and the Chita regions, Pg velocities decrease to about 6.1 km/sec, with a band of slightly lower velocities between 116° and 120°E. There are insufficient data to the northwest, in the Angara shield, to be meaningful.

It is interesting to note that velocities along the Baikal rift are slightly higher (Pg 6.20–6.28 km/sec, average 6.222 km/sec; Sg 3.59–3.61 km/sec) than in adjacent regions (Pg 6.125–6.175 km/sec, average 6.137 km/sec; Sg 3.55–3.57 km/sec). This difference is confirmed by travel-time curves calculated for arrivals at Nizhne Angarsk for events along the axis of the lake and from the east. Statistically, the curves are independent (Figure 3).

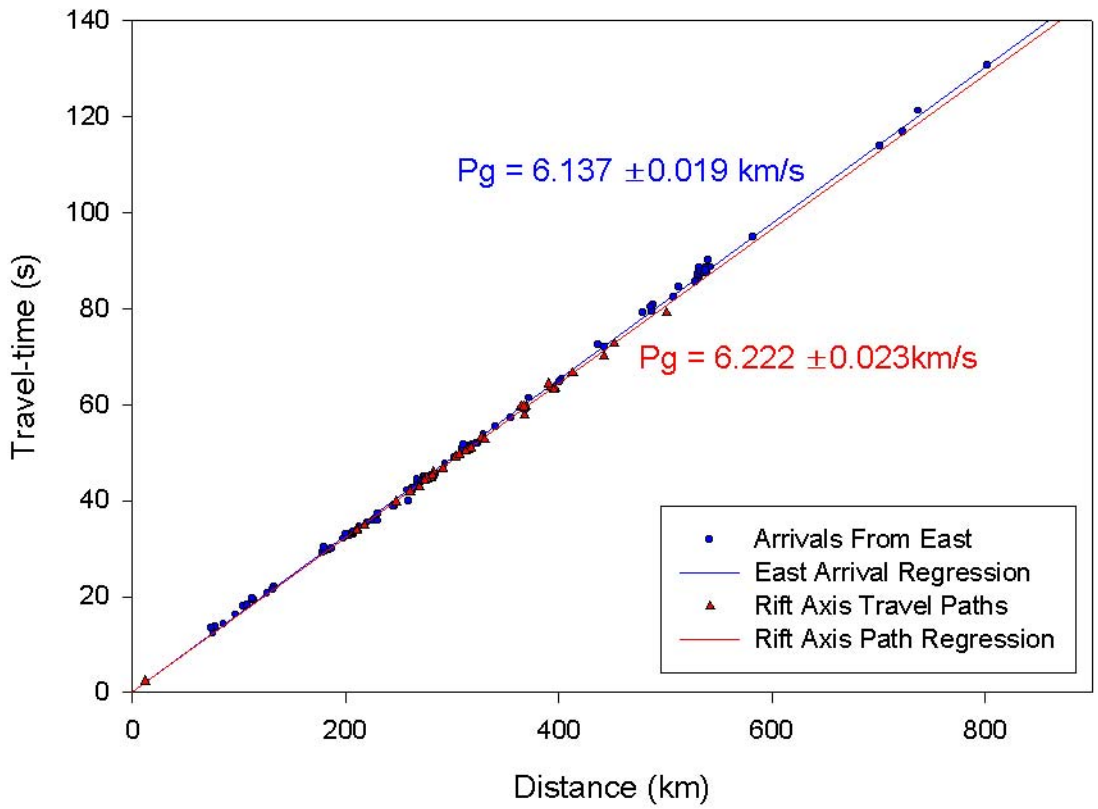

Figure 3. Pg Travel-time curve for Nizhne Angarsk (NIZ) showing a slightly faster velocity for arrivals traveling along the rift axis (red triangles) and a slower velocity for arrivals from the east (blue circles). Regression determined velocities noted on figure.

Russian refraction lines within Lake Baikal obtained a value of 6.2 ± 0.2 km/sec (Puzyrev, 1993, p. 149) for the top of the consolidated crust. The Ust'-Uda– and Ulan-Ude–Chita profiles yielded an average velocity for the upper crust (0–20 km) of 6.2 km/sec in the rift, decreasing to 6.1 km/sec to the southeast (Krylov et al., 1972; Suvorov et al., 2002); this profile shows an increase to 6.3 km/sec to then northwest in the Angara shield; however, we have insufficient data in that region. Long-range profiles using PNEs suggest similar results; data from the southern end of the RIFT profile indicate that the upper crustal velocities in the Baikal rift zone are similar to those in the Siberian craton, 6.2–6.3 km/sec (Pavlenkova et al., 2002). Travel-time curves for Pg and Sg based on Russian regional stations yield velocities of 6.17 ± 0.01 and 3.56 ± 0.02 km/sec, respectively (Golenetsky et al., 1978)—very much in agreement with our results.

Although upper mantle velocities in the Baikal rift show reduced seismic velocities as a result of hotter asthenosphere at shallower depths (Krylov and Duchkov, 1996), and there is a thick layer of low-velocity sediments near the surface (Krylov et al., 1972), our results, and those of the previous Russian studies, suggest that the upper crust is relatively unaffected seismically by the rifting process. This outcome may be a result of the narrowness of the rift and therefore its lack of resolution on our grid and on refraction profiles, or a result of mafic intrusions into the upper crust that increase the seismic velocity slightly.

To the southwest of Baikal, near Lake Khosgobul, Soviet refraction studies obtained upper crustal velocities of 6.3 km/sec (Zorin et al., 1993). Our data show 6.2 km/sec Pg velocities with a few cells having reaching 6.30–6.35 km/sec within northern Mongolia.

Northeast of Lake Baikal are a series of depressions that represent an extension of the Baikal rift system. We obtain Pg and Sg velocities in the region of these basins of 6.10–6.15 km/sec and 3.55–3.59 km/sec, respectively. Russian refraction studies indicate upper crustal Pg velocities in this region of about 6.1–6.2 km/sec (Puzyrev and Mandelbaum, 1984; Suvorov et al., 2002) and are calculated at 6.09-6.16 km/sec based on local earthquakes (Golonetsky et al., 1975). Suvorov and Kornilova (1985) obtained a slightly lower velocity of 6.0 km/sec for Pg in this region. Sg velocities from local earthquakes are 3.53–3.59 km/sec (Golonetsky et al., 1975). These velocities are slightly lower than in Lake Baikal proper and may be because of the fact that the rift is less well developed here. All studies show the increase in velocities near the Olekma River at the east end of the rift and the transition into the Aldan shield.

Southeast of Lake Baikal, in eastern Buryatia and the Chita region, we obtain Pg and Sg velocities of 6.08–6.15 km/sec and 3.55–3.57 km/sec, respectively. These velocities are slightly lower than in Lake Baikal or its northeastern extension. A thicker, low-velocity, upper crust is also obtained by Soviet refraction studies (e.g., Krylov et al., 1972; Krylov and Dychkov, 1996; Sun Youngsheng et al., 1996) and in mean velocity calculations for the upper crust (Suvorov et al., 2002). Average upper crustal Pg velocities as low as 5.9 km/sec are reported near Chita by Puzyrev and Mandelbaum (1984). Our results indicate that velocities are lowest slightly farther east, along 118–120°E, decreasing to 6.0–6.1 km/sec in Mongolia and near Hailar, China. Song et al. (1996) also obtain apparent velocities of about 6.12 km/sec near Hailar.

Amur District. We obtain slightly elevated velocities in the Amur district with Pg ranging from 6.0–6.2 km/sec and Sg values of 3.53–3.59 km/sec; these velocities are similar to those previously presented for this region in Mackey and Fujita (2000). One Soviet refraction line (Zeya—Bureya) crosses through the central Amur district, along a region where we obtain Pg values of 6.175–6.225 km/sec. The Soviet profile obtains upper crustal refraction velocities ranging from 5.8 to 6.4 km/sec with an upper crustal average velocity of 6.1 km/sec (Mishenkin et al., 1987).

Sakhalin Island. The velocities obtained for Sakhalin Island are very low, with Pg ranging from 5.65–5.85 km/sec and Sg between 3.3 and 3.47 km/sec. Travel-time curves for Nyvrovo (Figure 4), located on the north end of the island, for paths from the south, along the axis of Sakhalin, confirm this (Pg velocity of 5.70 km/sec). There is a sharp step in velocity with respect to the eastern Amur region where Pg velocities exceed 6.0 km/sec. Examination of travel-time curves from Nikolaevsk-na-Amur, located approximately on the boundary between the high- and low-velocity regions (Figure 5) also shows a clear difference with faster velocities (6.14 km/sec) to the west—in Amur.

A large number of refraction studies were conducted by the Soviet Union in Sakhalin and in the adjacent Sea of Okhotsk. These studies, however, do not indicate reduced velocities. The results of most of the Soviet surveys are summarized in Suvorov (1975), and include some contradictory interpretations. Two of the profiles run parallel to the island, profile 18 to the west of Sakhalin in the Tatar Strait, and profile 20 to the east, just offshore. Profile 20 yielded upper crustal velocities of 5.8 to 6.5 km/sec, with the lowest velocities near Hokkaido, Japan, while Profile 18, show highly variable refraction velocities for the upper crust ranging from 5.8 to 6.7 km/sec (Suvorov, 1975, p. 55, 67). Other cross-island profiles gave results of 6.1–6.8 km/sec. Volvovsky (1973) cites a velocity of 6.2 km/sec for northern Sakhalin, while Belyaevsky (1974) cites values of 6.0–6.1 km/sec for Sakhalin as a whole. These Russian studies all yield velocities higher than we obtain. The only exception is a profile shown by Gnibidenko (1979, p.42) that indicates a refractor with a velocity of 5.8–6.0 km/sec beneath northern Sakhalin.

On the other hand, Russian studies of travel times using local earthquakes consistently give velocities closer to that obtained in this study. Solovev et al. (1967) noted that travel times along the axis of Sakhalin fit closely to the 1939 Jeffreys-Bullen travel-time curve based on a 5.6 km/sec upper crustal velocity. A velocity model with a 5.6 km/sec upper crust derived from Maki (1983) is used in Sakhalin today. Additional studies using local earthquakes in Sakhalin by Nagornykh et al. (1988) yielded a Pg velocity of 5.73 ± 0.19 km/sec and an Sg velocity of 3.38 ± 0.09 km/sec, very close to our values presented above. Thus in Sakhalin there appears to be a difference between the Pg propagation velocity and what are considered upper crustal velocities observed on refraction lines. The reason for the low Pg velocities is unclear; much of Sakhalin is composed of sediments from the forearc of the Mesozoic Sikhote-Alin arc (e.g., Natalin and Parfenov, 1983) that became a zone of transpression resulting from the accretion of the Sea of Okhotsk (Jolivet et al., 1992). This accretion may have produced a thickened low velocity upper crust.

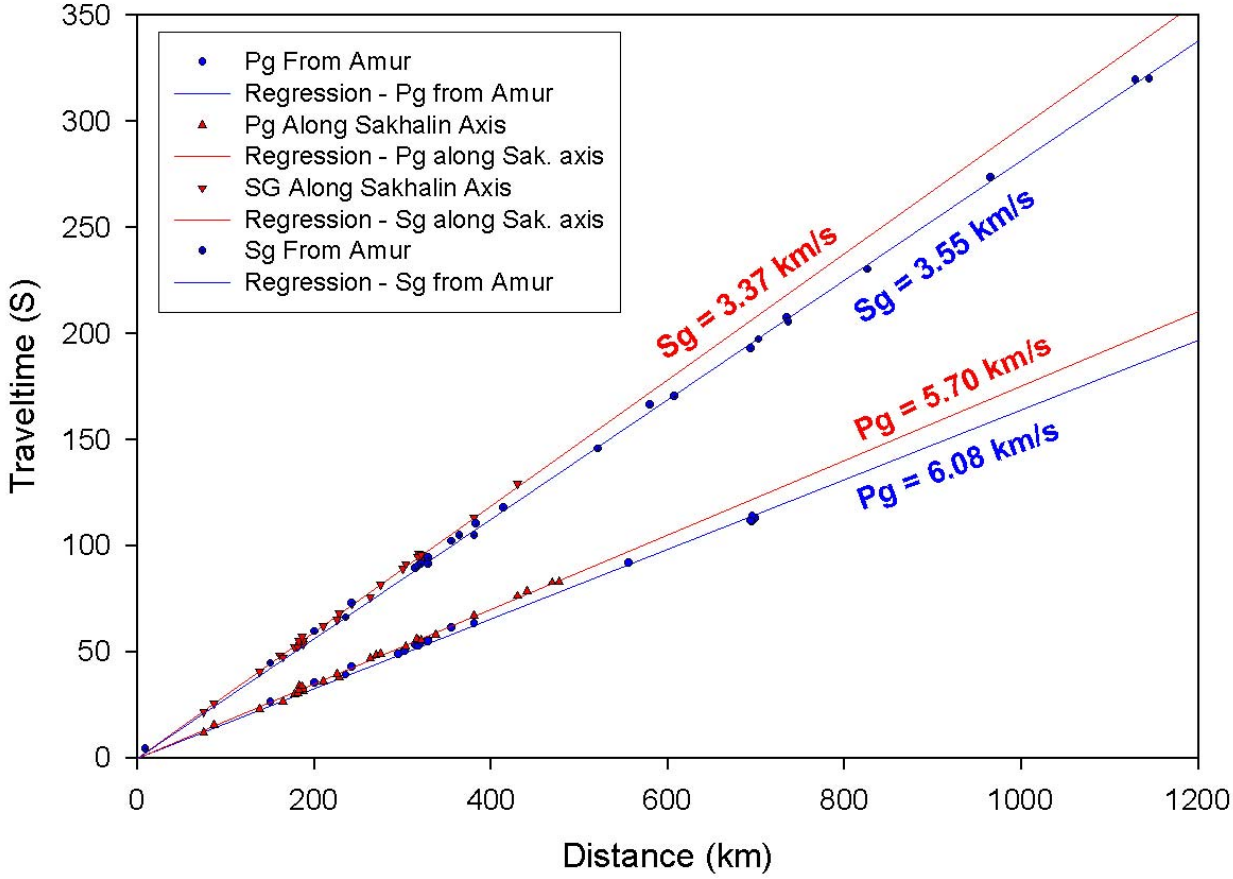

Figure 4. Station Nyvrovo (NVV) Pg and Sg travel-time curves comparing velocities for paths along Sakhalin Island axis (slow) and arrivals coming from the west (fast). Regression values are noted on figure.

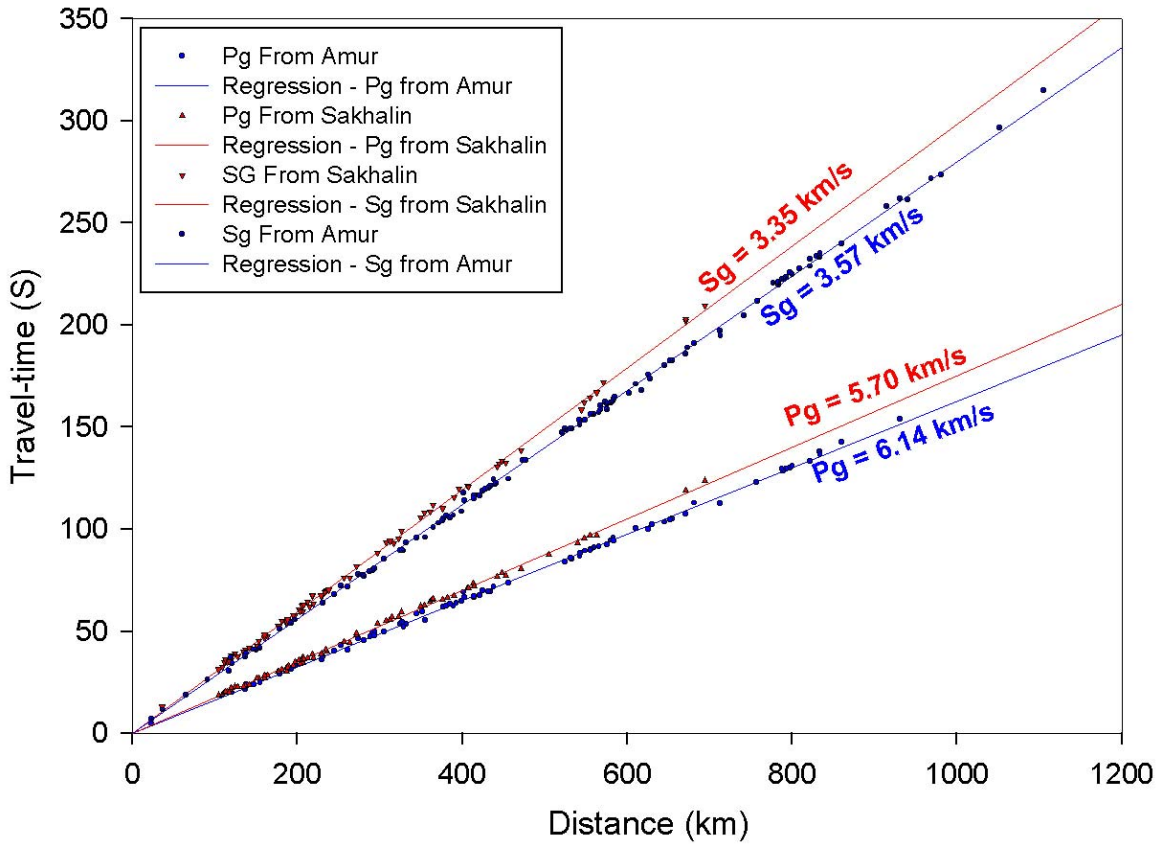

Figure 5. Station Nikolaevsk-na-Amur (NKL) Pg/Sg travel-time curves comparing velocities for paths from Sakhalin Island (slow) and arrivals coming from the west (Amur; fast). Regression values are noted on figure.

Figure 6 shows a summary of all phases identified as Pg, P*, and Pn (and corresponding S-phases) for Sakhalin as a function of epicentral distance. This figure shows a clear P* arrival at 6.39 km/sec between the Pg (5.72 km/sec) and Pn (7.88 km/sec) curves and suggests that what is identified as P* is the strong refractor observed in the refraction studies noted above.

The low-velocity region associated with Sakhalin appears to extend to the northern coast of the Sea of Okhotsk, where lower seismic velocities are also noted, especially for Sg.

Maritime Provinces. We have a limited amount of data from a cluster of earthquakes south of Lake Khaki that give velocities of about 6.1 km/sec. Russian refraction data here indicate a refractor with a velocity of 6.2 km/sec and an average upper crustal velocity of 5.8 km/sec (Argentov et al., 1976).

Based on the general consistency between the Pg values we have calculated and the refraction or average velocities in the upper crust obtained by Russian workers (except for Sakhalin), we conclude that the Pg phase reported by the regional networks is a phase that is sampling the upper continental crust, generally corresponding to velocities prevailing between 5 and 20 km depth. In Sakhalin, the Pg velocities are slower than the major refractor derived from deep seismic sounding studies; the latter appears to correspond to P*.

Event relocations

In conjunction with determining a new crustal velocity model, events used were simultaneously relocated. Relative to Russian network determinations, our relocations form tighter clusters and better defined fault lineations, suggestive of improved locations. Throughout the study area, events often move 5–15 km upon relocation, with the

exception of hypocenter determinations from the Irkutsk (Baikal) network. Relocations of Irkutsk network events generally move less than 5 km, indicating event locations determined by the Irkutsk network are probably better than locations provided by local networks in other regions of eastern Russia, possibly as a result of the denser regional network or use of a better-calibrated travel-time curve.

Digital station deployments

We continue development of our digital station network in northeastern Russia to improve epicenter locations and develop seismic discriminants in support of nuclear explosion monitoring by digitally recording local explosions and earthquakes. Deployment of these stations began under a previous project (Mackey et al., 2002). At present, we have twelve permanent stations deployed in and operated in conjunction with the Magadan Yakutsk, and Irkutsk networks of northeast Russia, four of which have opened this year. Several additional stations will open by fall of 2003. We also maintain three portable stations for explosion ground-truth acquisition and rapid deployment for aftershock sequence studies.

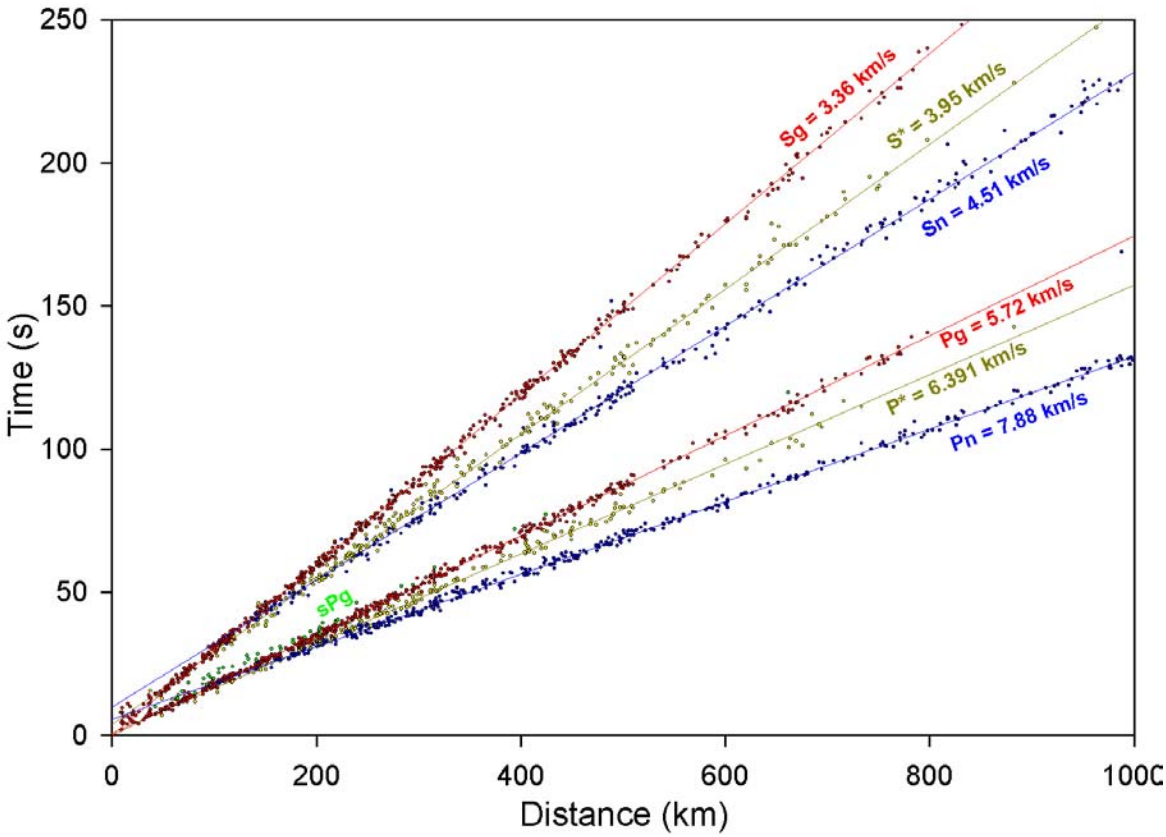

Figure 6. Composite travel time and regressions for Pg, P*, Pn, Sg, S*, and Sn phases reported from 92 Sakhalin earthquakes used in this study. Sakhalin data also include a significant number of additional local and regional phases, such as the sPg phase data plotted in green (others not shown).

CONCLUSIONS

We have now obtained a relatively detailed one-layer crustal velocity model for all of continental Siberia east of Lake Baikal. Pg and Sg velocities correspond to upper crustal velocities throughout the region and agree well with a wide variety of Russian studies, most of which are in the Baikal-Amur-Sakhalin regions. This agreement with smaller localized studies that exist in portions of our study lends support to our model for the remainder of the study area, particularly the Russian Far East. The analysis needs to be expanded into Kamchatka and, with the utilization

of additional events, may be extendable into less seismically active regions of continental eastern Siberia. A good understanding of Pg and Sg velocities is essential to improving hypocenter location abilities in eastern Russia as they are the dominant phases observed at local and regional distances out to about 600km.

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