CRUSTAL STRUCTURE OF NORTHEAST RUSSIA

K.G. Mackey, K. Fujita (Department of Geological Sciences Michigan State University East Lansing, MI 48824, USA), *L.J. Ruff* (Department of Geological Sciences University of Michigan Ann Arbor, MI 48109, USA)

ABSTRACT

The first order crustal structure of the Magadan region, northeast Russia, is obtained by simultaneously inverting for origin times and travel time curves. As an average, a 35 km thick, 6.00±0.01 km/sec crust overlying a 7.94±0.03 km/sec mantle provides an excellent fit to phase data listed in the Russian Siberian bulletin. Travel-time curves for individual stations are very close to this average, although there are some variations in crustal thicknesses and velocities; upper mantle velocities and crustal thickness appear to increase along the southern edge of the Okhotsk-Chukotka volcanic belt and decrease in the upper Kolyma River basin. In the Chersky Range, and at Ust'Nera, a crustal thickness greater than 30 km appears to fit the data best.

INTRODUCTION

Northeastern Russia is a region presently under compression and uplift as a result of the convergence of the North American and Eurasian plates (e.g., Naimark, 1976; Cook et al., 1986; Riegel et al., 1993). This region is composed of a series of exotic terranes which accreted in the Mesozoic (e.g., Parfenov, 1991) and then participated in an extensional episode in the Pliocene which resulted in the formation of the Moma rift system (Grachev, 1973; Fujita et al., 1990). As a result, the crustal structure of this region is expected to be very complex. Due to its general inaccessibility, however, very few seismic studies have been conducted in northeast Russia and the few available studies are based on isolated seismic refraction profiles, converted phases, and differential travel-times; none of the long-distance refraction lines conducted throughout the Siberian platform reached this area (Razinkova, 1987). Thus, the crustal structure is poorly known and some of the studies have contradictory results. In this paper we investigate the first order variations in crustal structure in northeast Russia using seismic wave travel time data from regional seismic events published in Russian seismic bulletins. The resolution of crustal thickness in this area will contribute to the understanding of the present-day tectonics of the area, the extent of rifting during the development of the Pliocene Moma rift, and on the nature of the North American and Eurasian plate boundary. In this paper, we confine ourselves to the area covered by the Magadan regional seismic network in the mid- to late-1980s. This region lies between 59-66°N, and 143-163°E and forms the central segment of the Chersky seismic belt (e.g., Koz'min, 1984; Parfenov et al., 1988). The study area lies primarily within the Okhotsk block which is undergoing deformation as it is compressed and extruded as a result of the convergence of the North American and Eurasian plates (Riegel et al., 1993; Riegel, 1994).

This region north of Magadan was selected for this study because of the relatively dense network of seismic stations, which should result in better focal parameters, the number of earthquakes, and due to the presence of a 350 km long deep-seismic sounding (refraction) line conducted in 1959 between Stekol'nyi, 50 km north of Magadan, and Ust'Srednikan on the Kolyma River (q.v., Ansimov et al., 1967). This line can be used to calibrate crustal studies and indicates a general thickening of the crust from 30 km at Stekol'nyi to 38 km on the Kolyma River, with a 6.0 km/sec crust, overlying a 8.1 km/sec mantle. In the northern part of this line, a 6.7 km/sec lower crust is also indicated (Ansimov et al., 1967). No direct data is available beneath Magadan, however, by extrapolation with an offshore refraction line, a Moho depth of 29-30 km is inferred (Ansimov et al., 1967).

Several previous studies have also considered this region. Suvorov and Kornilova (1986) used Russian bulletin data and travel time differences between seismic stations for common events to study crustal thickness and crustal and mantle velocities. Their results suggest crustal thicknesses increasing to the east (from 24 km at Ust'Nera to 38 km at Omsukchan) across our study area, and upper mantle velocities of 7.9 to 8.1 km/sec, generally increasing to the southeast. Their results are consistent with a significant Pliocene rifting episode which resulted in an elevated and lower velocity upper mantle; this result is supported by the surface wave polarization study of Lander (1984) which concludes that there is anomalous mantle under the Chersky Range. Suvorov and Kornilova (1986) also conclude that crustal (Pg) velocities are between 5.8 and 6.2 km/sec.

Studies of P to S near-receiver conversions, however, suggest a thickened crust, reaching 40 km at Ust'Nera, under the Chersky Range (Bulin, 1989). Results from Mishin and Dareshkina (1966), also attributed to Nikolaevsky by Belyaevsky (1974), yield crustal thicknesses between 30 and 34 km in the Kolyma gold belt (Table I). Additional stations, attributed to Mishin and Dareshkina (1966), are cited by Bobrobnikov and Izmailov (1989). Slightly different values, with crustal thicknesses closer to 40 km, are cited by Belyaevsky and Borisov (1974). A 38 km thick crust from deep seismic sounding in the upper Yama River valley and a regional 30-35 km thick crust, increasing to as high as 60 km southwest of the study area is reported by Bobrobnikov and Izmailov (1989).

Table I. Comparison of crustal thicknesses and velocities

Code	Station	Belyaevsky (1974)[1] km	Belyaevsky and Borisov (1974) km	Suvorov and Kornilova (1986) km	Suvorov and Kornilova (1986) Pn km/sec	This Study km	This Study Pg km/sec	This Study Pn km/sec
DBI	Debin	43[2]				33	6.08	7.90
EVE	Evensk	34[3]	40[3]			30	6.08	7.96
KU-	Kulu					29	6.02	7.73
MAG	Magadan		38	30±2[4]	8.1	40	6.04	8.13
MYA	Myakit					35	6.04	7.96
NKB	Nel'koba	39±14[5]	40			35	6.00	7.96
OMO	Omolon	38±17[5]	38			36	6.00	7.98
OMS	Omsukchan	30±12[5]	35	38±3		35	6.00	7.96
SEY	Seimchan			35±13	7.9-8.1	34	6.04	7.90
SNE	Sinegore					35	6.00	7.96
MGD	Stekol'nyi	31±9[5]	37			33	6.00	7.96
SUU	Susuman	50[2]	45 (?)	33±3	7.9-8.0	34	6.02	7.96
TTY	Takhtoyamsk					40	6.03	8.10
UNR	Ust'Nera[6]			24±3	8.0-8.1	30	6.00	7.91
REGIONAL						35	6.00	7.94

[1]Attributed to work by Nikolaevsky. [2]Values reported by Bobrobnikov and Izmailov (1989), apparently from the same study, although attributed to Mishin and Dareshkina. Bobrobnikov and Izmailov (1989) consider the value for Debin to be an error. [3]Data from Belyaevsky (1974) and Belyaevsky and Borisov (1974) for Garmanda, about 20 km north of Evensk. [4]Suvorov and Kornilova (1986) used Magadan as a calibration point based on the 1959 deep seismic sounding line. [5]Data and errors from Mishin and Dareshkina (1966). [6]For Ust'Nera, Bulin (1989) has determined crustal thickness to be 40 km.

Sedov and Luchinina (1988) used mine blasts along a profile between Tal-Yuryakh and Susuman to determine seismic velocities and layer thicknesses. The velocities obtained are somewhat different from the other studies cited above; a 5.5-5.6 km/sec upper crust overlying a 6.5-7.3 km/sec lower crust and an apparent Moho refraction of 10.6 km/sec. The high Moho velocity is attributed by them to a thinning of the crust in the direction of the profile; this end of the profile was not reversed.

METHODOLOGY AND REGIONAL CRUSTAL MODEL

For this study, travel time data from 50 well-locatable regional events occurring in the Chersky seismic belt north of Magadan during 1984-1989 were taken from *Materialy po Seismichnosti Sibiri*. Most of the stations considered are within 800 km of the epicenters.

All events were relocated using Pg arrivals only, assuming a 6 km/sec near surface layer, as well as first arrivals (Pg or Pn) using Jeffreys-Bullen travel-times. The particular epicenter used was dependent on the number of stations and resulting residuals; generally these were Pg solutions. Only events with more than eight arrivals were used in relocations. Our relocations provide better epicentral estimates; resulting numerical errors are on the order of 5 to 10 km and the amount of scatter in the Pg travel-time data is reduced. During the 1980s, most of the stations in this region used the "*Mayak*" system with timing accuracy of about 0.3 sec; combined with reading uncertainties, timing errors of 0.4-0.5 sec are expected. The events used in this study and the locations of the seismic stations are shown in Fig. 1. The travel-time data for our fifty best events as reported in *Materialy po Seismichnosti Sibiri*, using epicentral origin times reported there, are plotted in Fig. 2a. There is considerable scatter in the arrival times suggesting problems with the reported epicenters, phase identifications, or poor timing.

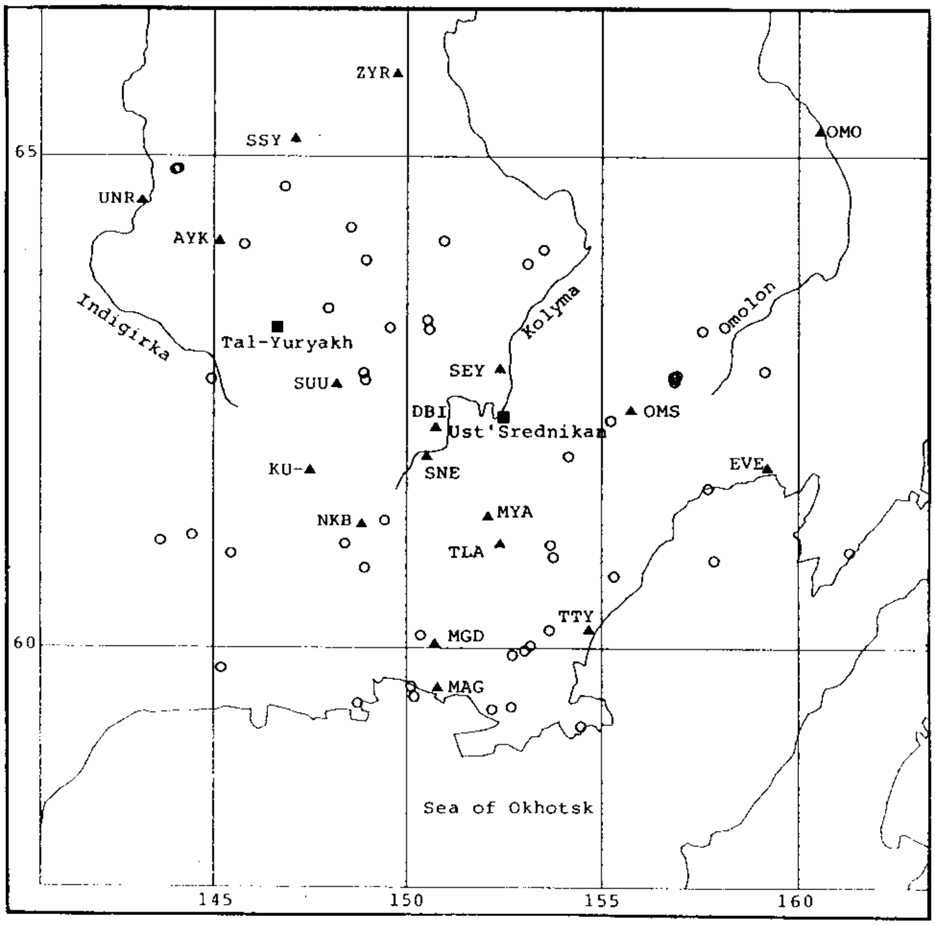
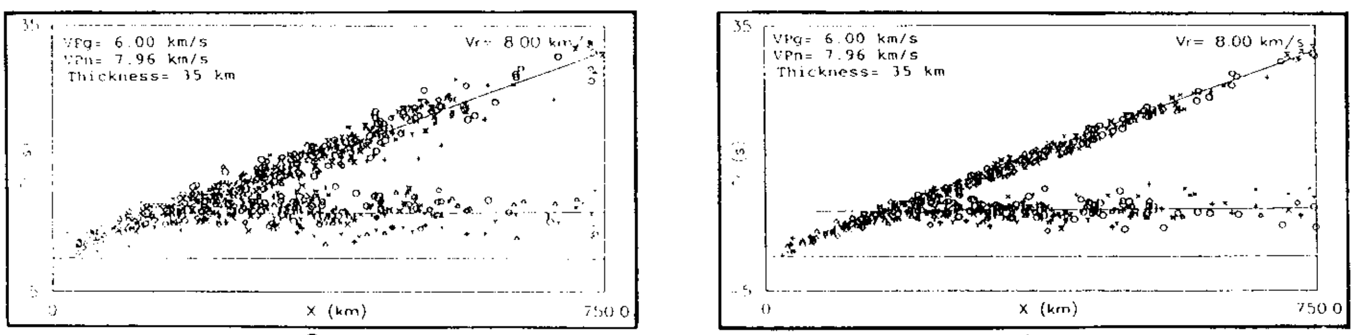


Fig. 1. Map of the study area showing relocated earthquakes (circles) and seismic stations of the Magadan and Yakut regional networks (triangles).

In order to determine the first-order crustal structure, we used the method of Ruff et al. (1994) which is a simultaneous inversion of travel times for both origin times and travel time curves, assuming fixed hypocenters. The Ruff method corrects, or accounts for, base-line timing errors, and depth and origin time uncertainties. The data set was examined using the relocated epicenters and inverted origin times in order to eliminate spurious arrivals (primarily stations discarded in the relocation process) and to isolate misidentified phases. The resulting data set was then inverted to produce our final regional model (Fig. 2b). Comparison of figures 2a and 2b show the reduction in data scatter resulting from use of the Ruff et al. (1994) method. As a result of this inversion, better estimates of the apparent velocities and crossover distances, and thus approximate crustal thickness, are obtained.



2a 2b

Fig. 2. a. P-wave data and reduced travel-time curves for the study area based on focal parameters presented in *Materialy po Seismichnost' Sibiri*. b. P-wave data and reduced travel-time curves for the study area based on origin times and velocity inversion using relocated epicenters with erroneous data removed. Best fit velocities in km/sec and crustal thicknesses are noted on the figures. Reduction velocity is 8 km/sec. Different symbols represent different events in figs. 2-6.

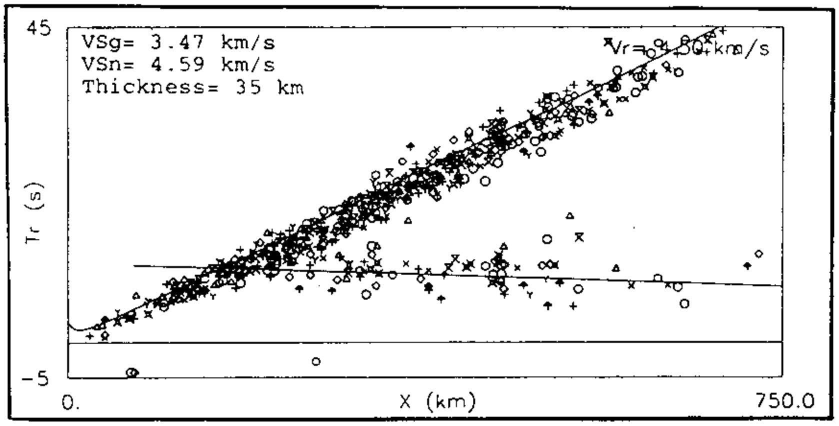


Fig. 3. S-wave data and reduced travel-time curves for the study area based on relocated epicenters and origin times from the inversion. Velocities in km/sec and crustal thickness are noted on the figure. Reduction velocity is 4.5 km/sec

Preliminary results for the Magadan region indicate a simple structure with a 5.996 ± 0.009 km/sec crust overlying a 7.96 ± 0.026 km/sec mantle. Average crustal thickness is about 35 km. Data at shorter epicentral distances (< 260 km) suggest a slightly higher Pg velocity of 6.127 ± 0.032 km/sec; the reason for this is not clear, although it may be related to misidentification of phases near the crossover distance. There is no clear evidence in the data to for a 6.7 km/sec lower crust as observed along the Magadan - Ust'Srednikan profile (Ansimov et al., 1967).

S-wave results, using the relocated epicenters and origin times from the inversion yield a Sg velocity of 3.47 km/sec and a Sn velocity of 4.59 km/sec (Fig. 3). The amount of scatter, and therefore the uncertainties, are greater than for the P-waves.

INDIVIDUAL STATIONS

We next examined the travel time curves for individual stations based on the relocated epicenters and inverted origin times, and estimated a best fit crustal structure. The use of only fifty events in our analysis results in a lack of data at many stations, and thus poorer determinations of velocities. Sufficient data were available for 14 stations, and our present data suggest that only minor structural variations exist between stations in the study area. The errors in determining crustal thickness appear to be ±4-5 km, Pg velocities, ±0.05 km/sec, and Pn velocities, ±0.1 km/sec. There is some trade off between Pn velocity and crustal thickness; higher velocities usually result in greater thicknesses. The use of additional events would greatly improve these determinations.

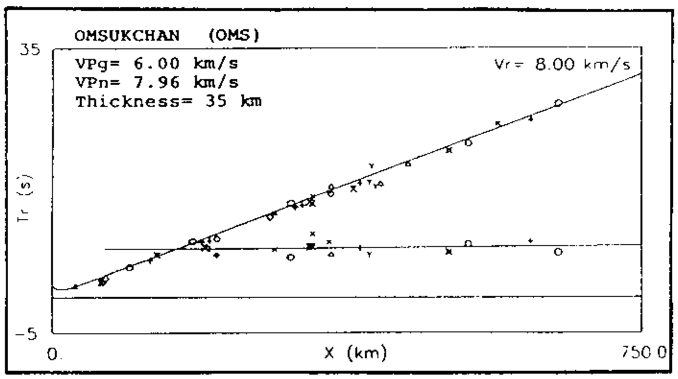


Fig. 4. P-wave data and reduced travel-time curves for Omsukchan based on relocated epicenters and inverted origin time. Conventions as in fig. 2.

Preliminary results (Tables I) suggest that velocities and thicknesses are very close to that determined to be the regional average. Most stations were fit well with a 7.96 km/sec Pn velocity and a 35 km depth (e.g., Omsukchan, Fig. 4). Magadan and Takhtoyamsk appear to have greater velocities (8.1 km/sec) and thicknesses (40 km), although both are constrained by a small number of observations. Significantly, both of these stations are located on the southern edge of the Okhotsk-Chukotka volcanic belt along a suture with the accreted Siglan arc (Watson and Fujita, 1985). Our results are also in good agreement with the deep seismic sounding results from the upper Yama River valley, also near this suture, reported by Bobrobnikov and Izmailov (1989). Ust'Nera (Fig. 5), and Kulu have lower velocities (7.7-7.9 km/sec) and slightly thinner crust (29-30 km); both of these stations are located in the western part of the study area. Debin, on the Kolyma, also exhibits a slightly lower Pn velocity, although the crustal thickness appears normal, while Evensk (Fig. 6), has normal velocities but a slightly thinner crust (30 km).

DISCUSSION

The Pn and Pg velocities obtained herein are in good agreement with the results of the Magadan-Ust'Srednikan refraction line (Ansimov et al., 1967; Belyaevsky, 1974). The crustal thicknesses (Table I) also agree fairly well with those reported by Belyaevsky and Borisov (1974) for Magadan, Omolon, and Omsukchan. Our results for Omsukchan, Seimchan, and Susuman also are in good agreement with Suvorov and Kornilova (1986).

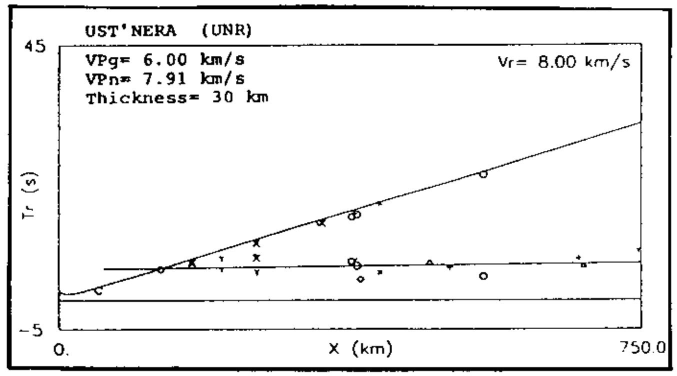


Fig. 5. P-wave data and reduced travel-time curves for Ust'Nera, stations with apparently thinner than average crust. Conventions as fig. 2.

The associated errors appear to be about half that of Suvorov and Kornilova (1986). One possible difference may result from the fact that Suvorov and Kornilova (1986) used data from before 1982, when epicentral determinations appear to be poorer. Suvorov and Kornilova (1986) assumed the thickness at Magadan using the refraction line, however, this result should correctly be applied at Stekol'nyi. The major differences between the various determinations are for Ust'Nera and Evensk, and perhaps Nel'koba. The Evensk data set presented here is one of the best in terms of epicentral distance coverage (Fig. 6) and the scatter in the data are very low, thus we feel that the 30 km crustal thickness is reasonable. It is possible to increase the thickness a few kilometers, which would put it in general agreement with the results of Nikolaevsky reported by Belyaevsky (1974).

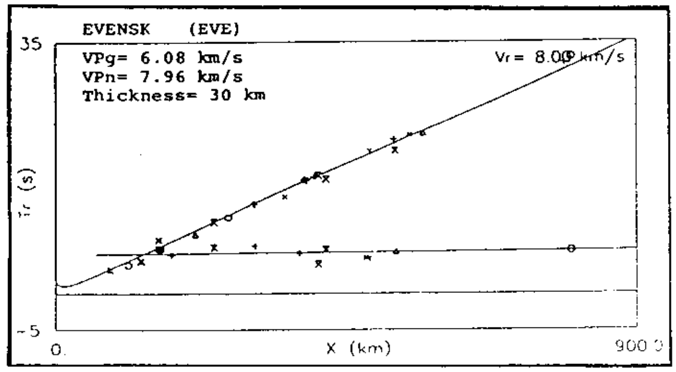


Fig. 6. P-wave data and reduced travel-time curves for Evensk. Conventions as in fig. 2.

The situation at Ust'Nera is more problematic. There is a great difference in the crustal thickness reported at Ust'Nera by Suvorov and Kornilova (1986), 24 km, and by Bulin (1989), 40 km. Our results fall somewhat in between at 30 km. Our results are strongly controlled by three events at epicentral distances of 700-800 km (Fig. 11b). Omission of this data would result in a higher Pn velocity and a thicker crust. Interpretation of the data does not, however, support a thinner crust; thus we are inclined to disagree with the results of Suvorov and Kornilova (1986). This may imply that the effects of the Moma rift are less than envisioned by Parfenov et al. (1988) and Lander (1984). Gravity analysis by Norton et al. (1994) also suggest a crustal thickness near Ust'Nera of 35-36 km.

CONCLUSIONS

The method of Ruff et al. (1994) allows us to obtain corrections for origin times and timing errors and rapid identification of spurious arrivals reported in the Russian bulletins. Combined with relocations of epicenters, this method has allowed us to refine the first-order crustal structure of northeast Russia using available phase data and to investigate crustal thickness and upper mantle velocities at individual stations. Our work confirms that a simple crustal model is sufficient to locate earthquakes in the region. Preliminary results suggest that there is no anomalously shallow upper mantle beneath the Chersky Range; the extension of this study will provide additional constraints on the tectonics and evolution of this highly complex region.

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