Seismic evidence for a moderately thick lithosphere beneath the Siberian Platform

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[1] We have built a *Sv*-wavespeed tomographic model for the upper mantle beneath the Siberian platform and surrounding region derived from the analysis of more than 13,000 fundamental and higher mode regional waveforms. The dense path coverage and rich higher mode content of the data allow building an upper mantle image with an horizontal resolution of a few hundred kilometers extending to ~400 km depth. The high velocity, upper mantle lid or seismic lithosphere is ~200 km thick beneath most of the Siberian platform but may extend to ~250 km depth beneath small areas. A high velocity seismic lid also underlies a large region west of the Siberian platform. Our observation of a ~200 thick seismic lithosphere beneath the Siberian platform on the slow-moving Eurasian plate, similar to the thickness of the seismic lithosphere beneath Precambrian terrains on the fast-moving Australian plate, suggests that a moderately thick seismic lithosphere beneath Precambrian terrains may be more common than previously supposed. *INDEX TERMS:* 7207 Seismology: Core and mantle; 7218 Seismology: Lithosphere and upper mantle; 7255 Seismology: Surface waves and free oscillations. **Citation:** Debayle, E., and K. Priestley, Seismic evidence for a moderately thick lithosphere beneath the Siberian platform, *Geophys. Res. Lett.*, *30*(3), 1118, doi:10.1029/2002GL015931, 2003.

1. Introduction

[2] Eastern Asia is a mosaic of ancient continental fragments separated by mountain ranges and fold belts. The crustal evolution of the largest Archean terrains, the Siberian platform (Figure 1), is thought to have started ~3.5 Ga, but the oldest rocks found thus far are ~3.3 Ga [*Jahn et al.*, 1998]. Initial seismic studies [*Lerner-Lam and Jordan*, 1983] suggest that the tectonically stable parts of northern Eurasia, including the Siberian platform, have a thick, high velocity lid extending to ~400 km depth; recent thermal modeling suggests that the thermal lithosphere [*Jaupart and Mareschal*, 1999] of the Siberian platform is ~350 km thick [*Artemieva and Mooney*, 2001].

[3] In this paper, we present a high-resolution shear velocity model of the upper mantle beneath NE Asia using more than 13,000 Rayleigh wave regional seismograms. The dense path coverage gives the model a lateral resolution of a few hundred kilometers, and the rich higher mode content of the events analyzed provides sensitivity down to ~400 km depth. Our model shows substantial variation in the thickness of the high velocity, upper mantle lid with values less than 100 km thick beneath tectonically active regions and values which may locally exceed 250 km beneath small parts of the Siberian platform. However, for most of the Siberian platform and the stable region to its west, the high velocity lid extends to 200–225 km depth. In this paper we equate the high seismic wavespeed "lid" to a "seismic" lithosphere [*Jaupart and Mareschal*, 1999], likely to be related to processes in the mantle of thermal and/or compositional origin (e.g., via depletion of the cratonic keel).

2. Development of the 3D Upper Mantle Velocity Model

[4] We construct the 3D upper mantle model using the two-step procedure previously used for Australia [*Debayle and Kennett*, 2000] and eastern Africa [*Debayle et al.*, 2001]. We first use the automated version [*Debayle*, 1999] of the *Cara and Lévêque* [1987] waveform inversion technique to determine a 1D path-average upper mantle velocity model compatible with observed surface waves. We then combine the 1D velocity models in a tomographic inversion using the continuous regionalization algorithm of *Montagner* [1986] to obtain the local *Sv*-wavespeed at each depth (see *Debayle and Kennett* [2000] for the details).

[5] The method is based on the assumptions that the observed surface waveform can be represented by multimode surface waves propagating independently and along the great circle. These assumptions are valid for a smoothly-varying medium without strong lateral velocity gradients [*Woodhouse*, 1974]. *Kennett* [1995] examined the validity of the path average approximation for surface wave propagation at regional continental scale and concluded that it should be suitable for periods between 30 and 100 s and remain valid at longer periods (>50 s) where surface waves cross major structural boundaries, such as the continent-ocean transition. Significant deviations from great-circle propagation have been observed for short periods (<40 s) surface waves [*Levshin and Ratnikova*, 1994; *Alsina and Snieder*, 1996; *Cotte et al.*, 2000], but surface wave ray tracing in Earth models [*Yoshizawa and Kennett*, 2002] similar to ours confirms that off-great circle propagation can reasonably be neglected for the fundamental and first few higher modes at periods greater than ~40 s and for paths less than ~10000 km. (Of the 13055 waveforms used to build our model, 74% have propagation path lengths less

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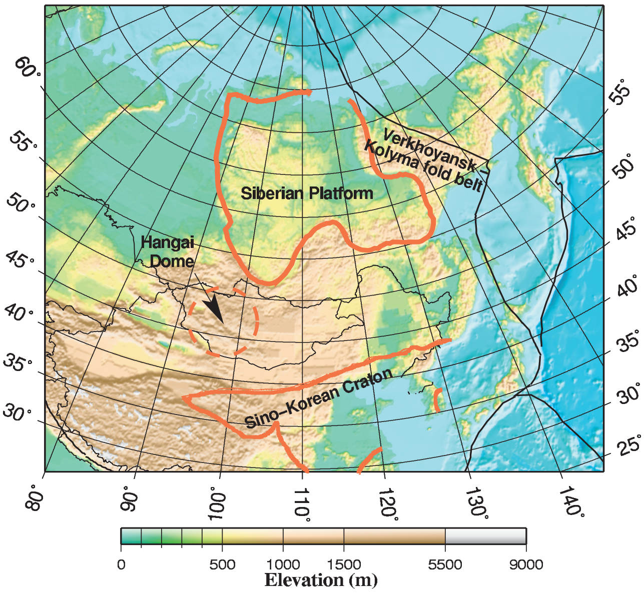

Figure 1. Map showing the tectonic elements of NE Asia discussed in the text. The contour of the cratons is taken from *Goodwin* [1991].

than 6000 km and only 24 waveforms have propagation paths lengths greater than 10000 km.) We therefore restrict our analysis to the fundamental and up to the fourth higher Rayleigh mode in the 50–160 s period band. Sensitivity kernels [see *Debayle et al.*, 2001] show that using the fundamental and up to the fourth higher mode in this period range achieves good sensitivity over the whole upper mantle. In addition, at 50 s period the maximum sensitivity of even the fundamental mode is located below the crust, so that our dataset is primarily sensitive to upper mantle structure.

[6] *Kennett* [1995] also showed that the source contribution is not confined to the immediate neighborhood of the epicenter and the source excitation computation is improved by using a structure specific to the source region. In computing the source excitation, we take the source region velocity structure from the 3D model 3SMAC [*Nataf and Ricard*, 1996] and analyze the seismograms using a smooth version of PREM as the reference and starting model for the upper mantle with a path-specific crustal model determined by averaging the crustal part of 3SMAC along the path. *Cara and Lévêque* [1987] show that for their technique, the final velocity structure is weakly dependent on the reference model. Since we analyze relatively long period surface waves (>50 s), we assume the crustal structure is known and invert for the upper mantle structure. To examine the effect of assuming different crustal models, we inverted a subset of the data assuming the 3SMAC and CRUST2 [*Bassin et al.*, 2000] crustal models; our results show no significant difference in the inversion models below ~100 km.

[7] In the continuous regionalization algorithm, the lateral smoothness of the inverted model is constrained by a horizontal correlation length L_{corr}. We choose L_{corr} = 400 km, thus favoring a smooth model considering our ray density and shortest wavelengths used (about 200 km at 50 s period). We tried various values of L_{corr} but even with L_{corr} = 800 km, the final model was smoother but the features of the model were essentially the same. Synthetic tests show that ray density allows us to resolve structures with horizontal wavelengths of a few hundred kilometers for the uppermost 400 km of the model. This agrees with the lateral resolution that can be expected when considering 'the influence zone of surface wave paths' over which surface waves are coherent in phase and which is identified as approximately one third of the first Fresnel zone [*Yoshizawa and Kennett*, 2002]. In the region lying outside the 'influence zone,' scattering effects can become important [*Spetzler et al.*, 2002] but in general, we did not observe evidence of scattering in the part of the waveforms we analyzed, suggesting that ray theory applies in our period range of analysis. In this paper, our goal is not

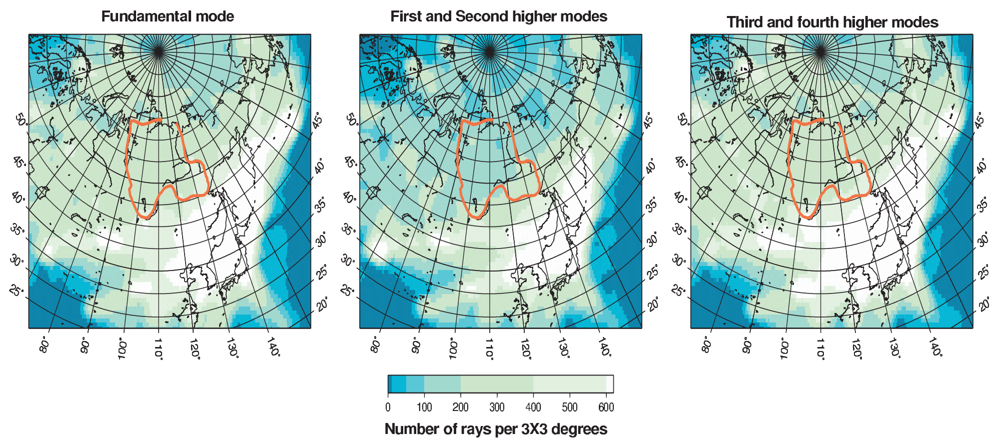

Figure 2. Path coverage maps. The dataset used to build the NE Asian model consists of 13,055 waveforms from 3671 earthquakes recorded at 51 seismographs. Ray density for 3° × 3° cells for the (a) 12310 fundamental mode paths; (b) 4180 first and 4957 second higher mode paths; and (c) 8225 third and 5930 fourth higher mode paths used in constructing the tomographic model. The dense ray coverage of 250–500 rays per 3° × 3° cell, the wide azimuthal distribution of the events, and the rich higher mode content of the data set permits building an image of the seismic lithosphere beneath the Siberian Platform with a horizontal resolution of a few hundred kilometers extending to ~400 km depth.

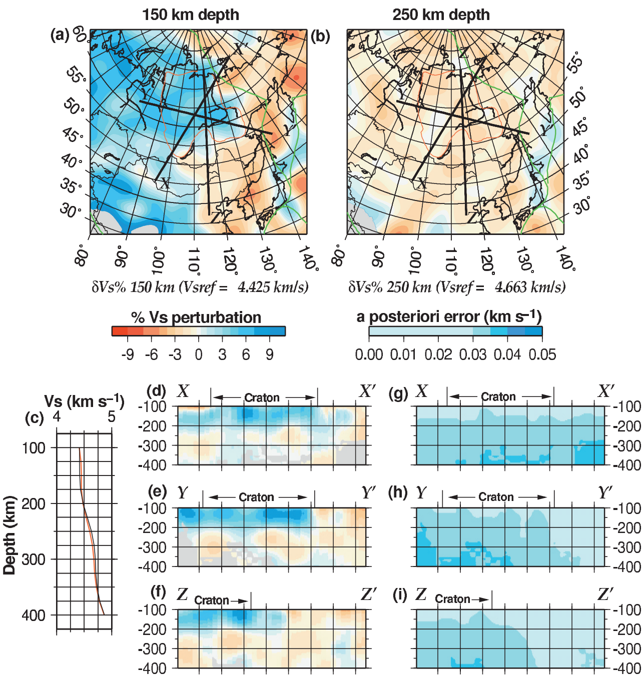

Figure 3. *Sv*-velocity heterogeneity model for NE Asia. (a) and (b) are depth slices through the model at 150 and 250 km depth. *Sv*-velocity perturbations in the depth slices are shown with respect to the PREM velocity at the corresponding depth. (d–f) are cross-sections in the *Sv*-velocity model for the great circles indicated on maps (a–b). The reference velocity for the cross-sections shown in (c) is the average of the seismic velocities of the inverted model at each depth (thick red line). For comparison, our initial smooth PREM reference model (thin black line) is also shown in (c). The cross-section profiles are 4242 km long and the vertical lines across the cross-sections are 500 km apart. The gray areas near the borders of the maps and cross-sections indicate the parts of the model where the a posteriori error is greater than 0.035. (g–i) show the a posteriori corresponding to the *Sv* profiles shown in (d–f). The low a posteriori error (<0.035), obtained compared to the a priori error (0.05), indicates good resolution down to 350–400 km depth for most of the cross-sections.

to interpret short wavelength heterogeneities, and we do not discuss here structures with wavelengths smaller than 1000 km.

3. 3D Model of NE Asia

[8] Figure 2 shows ray density for our model. Of the ∼80,000 seismograms analyzed, 13,055 seismograms from 3671 earthquakes recorded at 51 seismographs passed the stringent test of the automated waveform inversion [*Debayle*, 1999]. In a full synthetic experiment but with much lower higher mode coverage than shown in Figures 2b–2c, *Debayle et al.* [2001] demonstrated the ability of the *Cara and Lévêque* [1987] technique to isolate an anomaly located in the transition zone from the shallower and deeper structure. Depths and cross-sections for our model are shown in Figures 3a–3f; the a posteriori error for the cross-sections is shown in Figures 3g–3i.

[9] At 150 km depth (Figure 3a) the *Sv*-wavespeed varies by ±7% with high wavespeed beneath the stable, north-central parts of Asia, and low wavespeed beneath most of Mongolia, northeast China, and northeast Siberia. The lowest wavespeed upper mantle lies beneath the back arc basins to the west of the Kamchatka, Kuriles, and Japan volcanic arcs. The western part of the Sino-Korean Craton is underlain by high *Sv*-wavespeed upper mantle, but low wavespeed upper mantle lies beneath the eastern parts of the craton. Some of these features are noted in previous phase [*Trampert and Woodhouse*, 1995; *Ekstrom et al.*, 1997; *Curtis et al.*, 1998; *van Heijst and Woodhouse*, 1999] and group [*Ritzwoller and Levshin*, 1998] velocity maps of Asia. At 250 km depth (Figure 3b) the range in wavespeed has decreased to ±3% and the strong division between high wavespeed beneath the stable region of north-central Asia and low wavespeed beneath the tectonically active areas has disappeared.

[10] The vertical cross-sections (Figures 3d–3f) show significant lateral variations in the thickness of the high velocity lid. It is well known that in regions where the resolution is low, the a posteriori error nearly equals the a priori error [*Tarantola and Valette*, 1982]. Because of the large number of higher modes included in the analysis, the a posteriori error is low (<0.035 km s^{-1}) compared to the a priori error (set at 0.05 km s^{-1}) over most of the cross-sections (Figure 3g–3i), indicating that we have good resolution to at least 350 km depth. The Hangai Dome in western Mongolia is underlain by a low *Sv*-wavespeed at shallow depth (<125 km) but high *Sv*-wavespeed at greater depths. Using the strongest negative gradient in *Sv*-wavespeed as an indicator for the bottom of the high velocity lid, we estimate the upper mantle lid base to lie between 175 and 225 km depth beneath most of the Siberian platform. However, a thicker lithosphere may exist beneath isolated parts of the Siberian platform.

4. Discussion and Conclusions

[11] *Lerner-Lam and Jordan* [1983] suggest that the tectonically stable part of northern Eurasia, including the Siberian platform, has a thick seismic lithosphere extending to ∼400 km depth. *Artemieva and Mooney* [2001] found the thermal lithosphere beneath the Siberian platform to be ∼350 km thick. Our model, based on an unprecedented higher mode regional waveform dataset, shows that the seismic lithosphere, as defined by the high velocity lid, is moderately thick beneath most of the Siberian platform, in better agreement with recent global tomography [*Ritsema and van Heijst*, 2000a] which includes higher modes for good vertical resolution, but with weaker horizontal resolution compared to this study. A moderately thick (∼200 km) seismic lithosphere agrees well with the thermal structure proposed for the Siberian platform from petrologic modeling of upper mantle nodules from Siberian kimberlites [*Pearson et al.*, 1995]. Isolated high wavespeed anomalies extend down to ∼250 km beneath small regions of the Siberian platform and these features may partially reconcile our seismic model with the thermal model of *Artemieva and Mooney* [2001].

[12] High velocity seismic lithosphere, although attenuated, persists to the west of the Siberian platform in our model, similar to that seen in recent global models [*Ritsema and van Heijst*, 2000a]. This observation is compatible with

cratonic-like basement lying buried beneath the west Siberian basin [D. Ionov, personal communications, 2002]. *Debayle and Kennett* [2000] found that the thickness of the high velocity lid beneath the fast-moving Australian plate oscillates around 200 km, and *Ritsema and van Heijst* [2000b] find a similar lid thickness beneath the cratons on the slow-moving African plate. Our finding of a comparable lid thickness beneath the Siberian platform on the slow-moving Eurasian plate suggests that very thick cratonic roots may be less common than previously supposed.

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