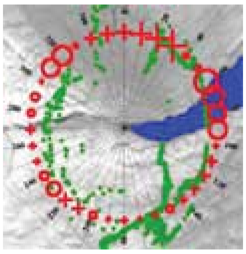

Mantle transition zone discontinuities beneath the Baikal rift and adjacent areas

Kelly H. Liu & *Stephen S. Gao*

Department of Geological Sciences and Engineering, University of Missouri-Rolla

liukh@umr.edu

Modified from: Liu, K.H. and S.S. Gao (2006), Mantle transition zone discontinuities beneath the Baikal rift and adjacent areas, *J. Geophs. Res.*, **111**, B11301, doi:10.1029/2005JB004099.

Click here to go to Discussion of this page

Introduction

The Baikal rift zone (BRZ) in Siberia is a major continental rift zone. This 1500-km-long *en echelon* system of rift depression, which originated about 35 Ma ago along the boundary between the Archean Siberian platform and the Paleozoic-Mesozoic Altai-Sayan-Baikal foldbelt, is the most seismically active continental rift in the world [*Logatchev & Zorin*, 1992; *Keller et al.*, 1995] (Figure 1). Similar to most other major continental rifts, the BRZ is characterized by higher than normal heat flow [*Lysak*, 1984], negative gravity anomalies [*Zorin et al.*, 1989], and thinned crust [*Zorin et al*. 2002; *Gao et al.*, 2004]. Rift-orthogonal mantle flow associated with the rifting and rift-parallel magma-filled cracks beneath the BRZ are suggested by measured shear-wave splitting parameters [*Gao et al*., 1994a; 1997] and inversion of *P*-wave arrival times [*Gao et al.*, 2003]. [Ed: for more on the Baikal rift, see also Diffuse, long-lived Cenozoic volcanism in Mongolia, Topography, geoid and gravity anomalies in Western Mongolia and One rift, two models.]

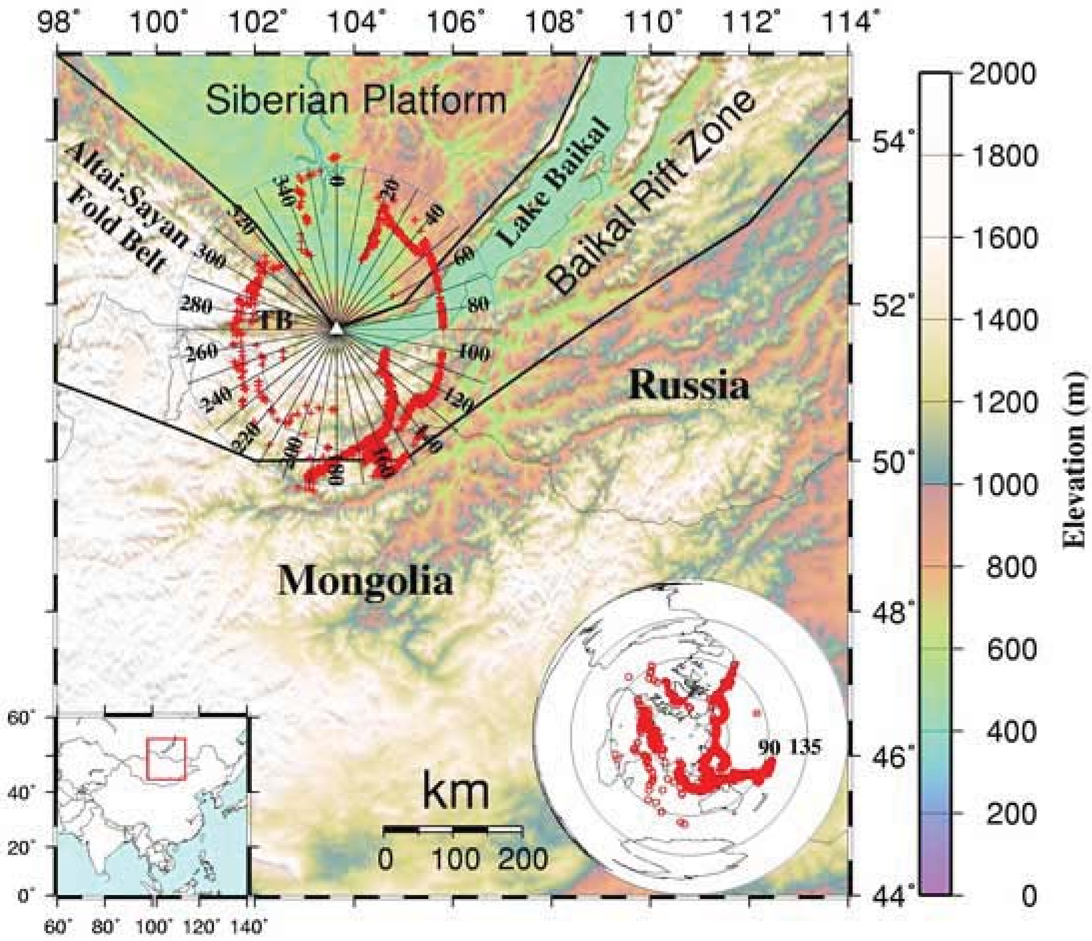

Figure 1. Topographic map of the study area showing tectonic provinces, distribution of ray-piercing points at 540 km depth (crosses), and azimuthal bins. The bins have a width of 20° and overlap by 10°. Consequently, the central azimuth of the nth bin is 10n degrees from North. Station TLY is represented by the open triangle, and TB is the Tunkin Basin. Tectonically the BRZ is a domal structure in the Altai-Sayan-Baikal foldbelt. In this study we refer to the part of the foldbelt west of bin 15 as the Altai-Sayan foldbelt, and to the eastern part with rifted valleys as the BRZ. The insets show the location of the study area, and the epicenters of the earthquakes used in the study.

While most other continental rifts such as the Rio Grande and East African rifts are found to be underlain by a low velocity zone in the upper mantle and even the mantle transition zone (MTZ, 410-660 km depth range) [*e.g.*, *Davis*, 1991; *Slack et al.*, 1996; *Achauer & Masson*, 2002; *Wilson et al.*, 2005a], contradictory seismic tomography results were obtained for the BRZ. Most studies suggest low seismic velocities in the upper mantle beneath the rift [*e.g.*, *Gao et al*., 1994b; 2003; *Achauer & Masson*, 2002; *Friederich*, 2003; *Brazier & Nyblade*, 2003; *Tiberi et al*., 2003; *Zhao et al.*, 2006], but others did not find such anomalies [*e.g.*, *Petit et al.*, 1998]. The depth extent of the low-velocity anomaly differs greatly among the studies, from less than 100 km to as deep as 600 km. Some studies suggested a plume-like low-velocity cylindrical anomaly extending from about 135 km to the MTZ [*Friederich*, 2003], while others indicated a depth extent of about 700 km [*Petit et al.*, 1998]. [Ed: see also Topography, geoid and gravity anomalies in Western Mongolia by *Petit et al*. 2005.]

The present study is aimed at measuring the spatial variation of the depth to the 410 km discontinuity (*d*410) and the 660 km discontinuity (*d*660) in the vicinity of the BRZ and the Siberian platform. The objective is to provide additional constraints on the deep structure, temperature, and dynamics of the rift.

Data and Method

The broadband seismograms used in the study were recorded by GSN station TLY (Talaya, N51.6807°, E103.6438°, elevation 579 m). Seismograms from teleseismic events (epicentral distances 30° to ~100°) that occurred between May 1991 and September 2005 were converted to radial receiver functions (RFs) using the procedure of *Ammon et al.* [1990], i.e., deconvolving the radial component with the vertical component. A total of 1718 high-quality RFs were used in the study (Figure 2). We use the RF-stacking approach of *Dueker & Sheehan* [1998] to enhance the weak *P*-to-*S* converted phases originating from the top and bottom discontinuities of the MTZ (Figure 3). The bootstrap resampling procedure [*Press et al.*, 1992; *Efron & Tibshirani*, 1986] was used to estimate the standard deviations (STDs) of the discontinuity depths.

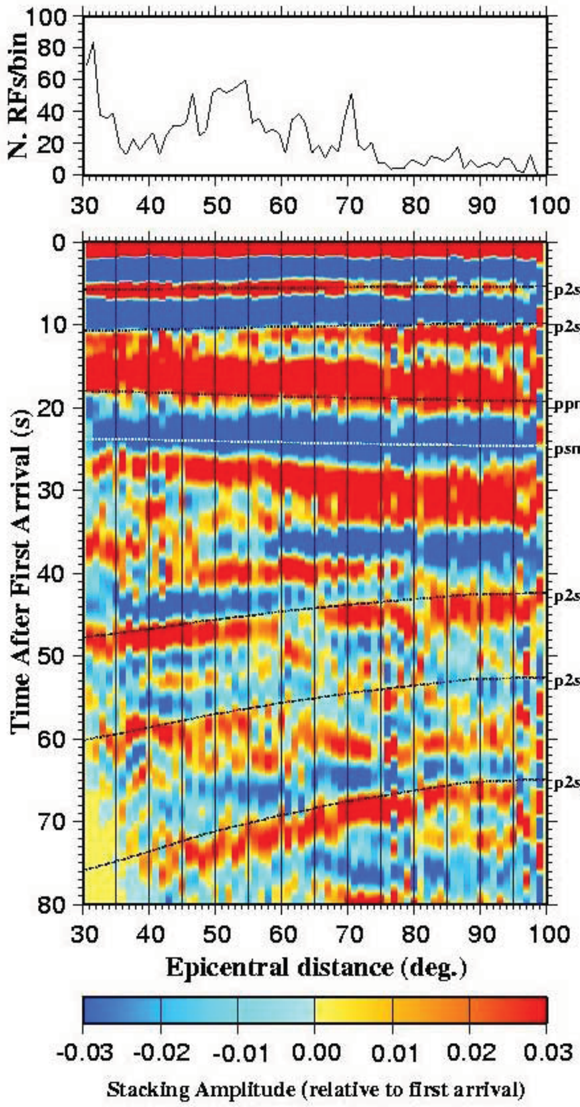

Figure 2. The bottom plot shows stacked radial receiver functions. The 1718 radial receiver functions used in the study are arranged according to their depth-corrected epicentral distances into 1° ranges and those in the same range are then stacked. The dashed lines labeled as P2S_xyz are predicted moveout curves for P-to-S converted phases at depth xyz km, and the lines labeled ppms_046 and psms_046 are the Moho (which has a depth of 46 km) reverberation phases PPmS and PSmS, respectively. The top plot shows the number of receiver functions per bin.

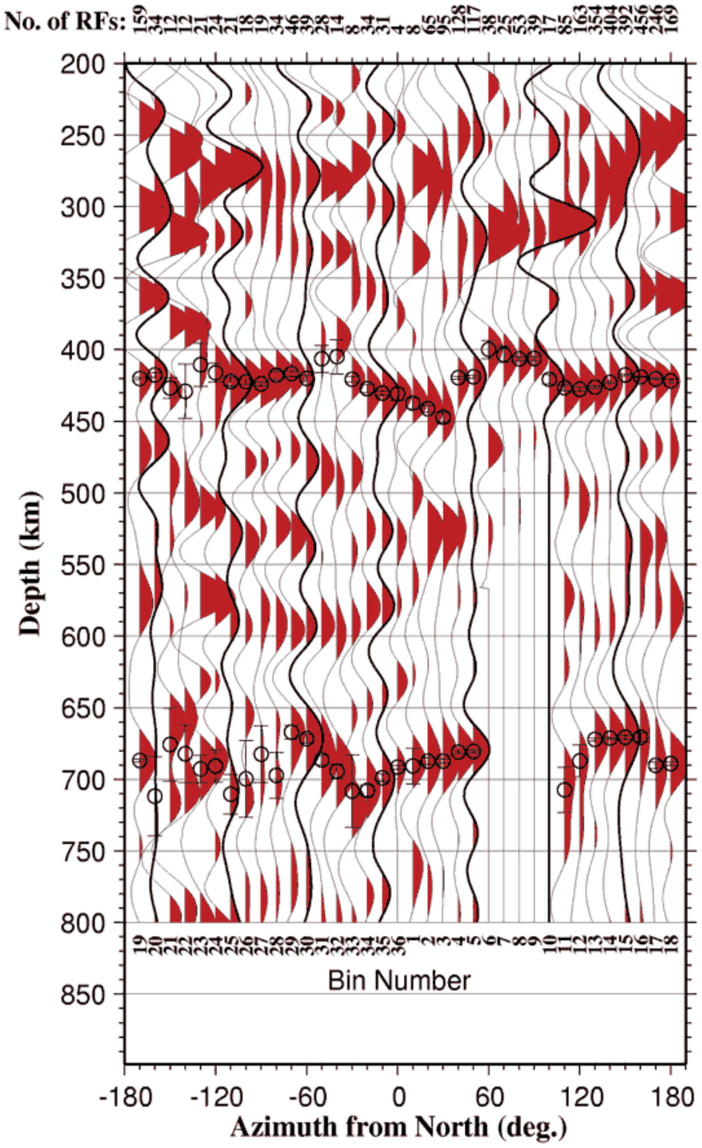

Figure 3. Results from stacking radial receiver functions beneath the azimuthal bins. Positive polarities of the traces are shaded. The traces were normalized by the average of the maximum amplitudes in the 400-450 and 660-720 depth ranges. The top row shows the number of receiver functions per bin at 540 km depth. Mean depths and their STDs from the bootstrap steps are shown as circles and bars in the 400-450 and 650-700 km depth ranges.

Results and Discussion

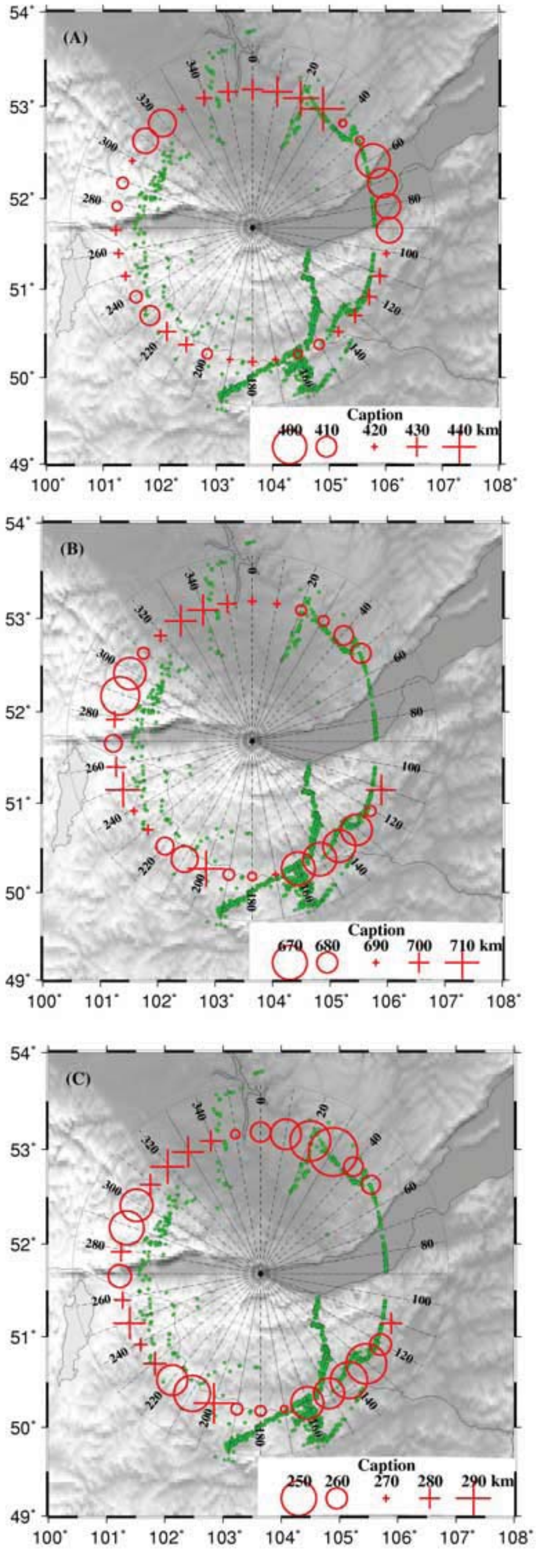

Figure 4. (A) depth to d410; (B) depth to d660; (C) MTZ thickness for each of the azimuthal bins. Green stars are ray piercing points at 540 km depth.

1. The 410 km Discontinuity (d410)

Figure 4A: The depth to *d*410 varies from 400 ± 6 km to 447± 4 km. The mean depth is 421± 2 km, which is slightly deeper than the global average of 418 km [*Flanagan & Shearer*, 1998]. Beneath the Altai-Sayan fold belt, *d*410 is relatively flat with a depth that is close to the mean. A significant deepening of *d*410 toward the rift axis with a magnitude of about 25 km is observed beneath the Siberian platform, corresponding to an increase in mantle temperature of about 300°C in the vicinity of the *d*410 [*Dueker & Sheehan*, 1998; *Gao et al.*, 2002; *Shen et al.*, 2002; *Liu et al.*, 2003]. An uplift of the *d*410 is found beneath the lake with a magnitude of 47 km, corresponding to a temperature reduction of about 550°C beneath the rift relative to the south margin of the platform.

2. The 660 km Discontinuity (d660)

Figure 4B: The mean depth of *d*660 (688± 2 km) is significantly greater than the global average of 660 km [*Flanagan & Shearer*, 1998]. An uplift of *d*660 is observed beneath the foldbelt, centered near the Tunkin Basin. The southern half of the uplift, however, cannot be well-determined due to the small number of RFs and resulting large STDs. If the uplift is confirmed using additional data, it suggests a thermal anomaly with a lateral temperature contrast of several hundred degrees at the bottom of the MTZ. A possible cause of the anomaly is a mantle plume that has not reached *d*410. Beneath the platform, *d*660 shallows gradually toward the rift, from 708 km to 681 km, corresponding to a temperature increase of about 460°C.

3. MTZ Thickness

Figure 4C: The thickness of the MTZ in our study area ranges from 240 to 293 km, with a mean of 264± 3 km, suggesting a colder MTZ on average. The MTZ beneath the platform thickens gradually toward the interior of the platform, from 240 km to 290 km. This corresponds to a decrease in temperature of about 380°C. The variations in *d*410 and *d*660 contribute to the thickening of the MTZ approximately equally, suggesting that the temperature of the entire MTZ decreases toward the interior of the platform.

Beneath the lake, the depth extent of the thickened region (relative to the platform) suggested by the uplifted *d*410 cannot be accurately determined due to the lack of seismic rays that traverse *d*660. If we assume that the lateral temperature anomaly in the entire MTZ is uniformly –550°C, as suggested by the magnitude of the uplift of *d*410, an approximately 30-km depression of *d*660 is expected. This is comparable to the magnitude of the deepening of *d*660. Under the assumption that $dV_p/dT = -4.1 \times 10^{-4}$ km/s°C [*Anderson*, 1989], the increase in *P*-wave velocity is about 0.2 km/s, corresponding to a 2% high velocity anomaly in the MTZ. The observed variation of the MTZ thickness is consistent with seismic tomography results. Although most seismic tomography studies [*e.g.*, *Achauer & Masson*, 2002; *Gao et al*., 1994, 2003; *Tiberi et al*., 2003] revealed low-velocity regions in the upper mantle beneath the rift, there is still a lack of strong evidence for such anomalies extending to the MTZ. On the contrary, a recent seismic tomography study by *Zhao et al*. [2006] suggested a high velocity region with a magnitude of 1-2% in the MTZ beneath the rift.

The possible mechanism for the observed transition zone discontinuity topography is thermal anomalies associated with the rifting process. The observed uplift of *d*410 and depression of *d*660 beneath the BRZ suggest a MTZ that is colder than the surrounding areas. The uplift of *d*410 rules out the possibility that the rifting is due to a mantle plume originating below *d*410. However, the possibility that the rifting is related to a plume originating in the upper mantle cannot be excluded based on existing data. To our knowledge, this is the first time that a cold MTZ is suggested beneath a major continental rift, and so far no existing geodynamic or mineralogical models can explain this unexpected result. Previous seismic tomography results and the characteristics of the RFs presented in this study do not support the hypothesis that the uplift of *d*410 is caused by excess water in the top of the MTZ. One possible cause of the low temperature in the MTZ is that the opening of the rift at about 35 Ma created a zone of high surface heat flux [*Lysak*, 1984] and partial melt (and consequently reduction in seismic velocity) in the upper mantle beneath the rift. This model, however, must remain quite speculative until additional information regarding the thermal history and thermal properties beneath the study area can be obtained so that vigorous geodynamic modeling can be performed.

In summary, using data from a single broadband station, we have imaged spatial variation of mantle transition zone discontinuities. The main features are the unexpected uplift of the *d*410 and possible depression of *d*660, suggesting a reduced temperature and increased velocity with a magnitude of 2% in the mantle transition zone beneath the BRZ relative to the southern margin of the Siberian platform. We also observed a gradual cooling of the MTZ beneath the Siberian platform toward its interior.

References

- Achauer, U., and F. Masson (2002), Seismic tomography of continental rifts revisited: from relative to absolute heterogeneities, *Tectonophysics*, **358**, 17-37.
- Ammon, C.J., G.E. Randall, and G. Zandt (1990), On the non-uniqueness of receiver function inversions, *J. Geophys. Res*., **95**, 15,303-15,318.
- Anderson, D.L. (1989), *Theory of the Earth*, Blackwell Scientific Publications, Boston.
- Brazier, R.A., and A.A. Nyblade (2003), Upper mantle *P* velocity structure beneath the Baikal Rift from modeling regional seismic data, *Geophys. Res. Lett.*, **30**, 1153, doi:10.1029/2002GL016115.
- Davis, P.M. (1991), Continental rift structures and dynamics with reference to teleseismic studies of the Rio Grande and East African rifts, *Tectonophysics*, **197**, 309-325.
- Dueker, K.G., and A.F. Sheehan (1998), Mantle discontinuity structure beneath the Colorado Rocky Mountains and High Plains, *J. Geophys. Res*., **103**, 7153-7169.
- Efron, B., and R. Tibshirani (1986), Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy, *Stat. Sci*., **1**, 54-75.
- Flanagan, M.P., and P.M. Shearer (1998), Global mapping of topography on transition zone velocity discontinuities by stacking SS precursors, *J. Geophys. Res*., **103**, 2673-2692.
- Friederich, W. (2003), The *S*-velocity structure of the East Asian mantle from inversion of shear and surface waveforms, *Geophys. J. Int.*, **153**, 88-102.
- Gao, S., P.M. Davis, H. Liu, P.D. Slack, Y.A. Zorin, V.V. Mordvinova, V.M. Kozhevnikov, and R.P. Meyer (1994a), Seismic anisotropy and mantle flow beneath the Baikal rift Zone, *Nature*, **371**, 149-151.
- Gao, S., P.M. Davis, H. Liu, P. Slack, Y.A. Zorin, N.A. Logatchev, M. Kogan, P. Burkholder, and R.P. Meyer (1994b), Asymmetric upwarp of the asthenosphere beneath the Baikal rift zone, Siberia, *J. Geophys. Res*., **99**, 15,319-15,330.
- Gao, S., P.M. Davis, H. Liu, P.D. Slack, A.W. Rigor, Y.A. Zorin, V.V. Mordvinova, V.M. Kozhevnikov, and N.A. Logatchev (1997), SKS splitting beneath continental rift zones, *J. Geophys. Res*., **102**, 22,781-22,797.
- Gao, S.S., P.G. Silver, and K.H. Liu (2002), Mantle Discontinuities Beneath Southern Africa, *Geophys. Res. Lett*., **29**, 1491, doi: 10.1029/2001GL013834.
- Gao, S.S., K.H. Liu, P.M. Davis, P.D. Slack, Y.A. Zorin, V.V. Mordvinova, and V.M. Kozhevnikov (2003), Evidence for small-scale mantle convection in the upper mantle beneath the Baikal rift Zone, *J. Geophys. Res*., **108**, 2194, doi:10.1029/2002JB002039.
- Gao, S.S., K.H. Liu, and C. Chen (2004), Significant crustal thinning beneath the Baikal rift zone: New constraints from receiver function analysis, *Geophys. Res. Lett.*, **31**, 20610, doi:10.1029/2004GL020813.

- Keller, G.R., M. Bott, R.F. Wendlandt, D.I. Doser, and P. Morgan (1995), The Baikal rift system, in *Continental rifts; evolution, structure, tectonics*, Elsevier, Amsterdam.
- Liu, K.H., S.S. Gao, P.G. Silver, and Y.K. Zhang (2003), Mantle layering across central South America, *J. Geophy. Res.*, **108**, 2510, doi:10.1029/2002JB002208.
- Logatchev, N.A., and Y.A. Zorin, Y.A. (1992), Baikal rift zone - structure and geodynamics, *Tectonophysics*, **208**, 273-286.
- Lysak, S.V. (1984), Terrestrial heat flow in the south of east Siberia, *Tectonophysics*, **103**, 205-215.
- Petit, C., I. Koulakov, and J. Deverchere (1998), Velocity structure around the Baikal rift zone from teleseismic and local earthquake travel-times and geodynamic implications, *Tectonophysics*, **296**, 125-144.
- Shen, Y., S.C. Solomon, I. Th. Bjarnason, G. Nolet, W.J. Morgan, R.M. Allen, K. Vogfjord, S. Jakobsdottir, R. Stefansson, B.R. Julian, and G.R. Foulger (2002), Seismic evidence for a tilted mantle plume and north-south mantle flow beneath Iceland, *Earth Planet. Sci. Lett.*, **197**, 261-272.
- Slack, P.D., P.M. Davis, W.S. Baldridge, K.H. Olsen, A. Glahn, U. Achauer, and W. Spence (1996), The upper mantle structure of the central Rio Grande Rift region from teleseismic P and S wave travel time delays and attenuation, *J. Geophys. Res.*, **101**, 16,003-16,023.
- Tiberi, C., M. Diament, J. Deverchere, C. Petit-Mariani, V. Mikhailov, S. Tikhotsky, and U. Achauer (2003), Deep structure of the Baikal rift zone revealed by joint inversion of gravity and seismology, *J. Geophys. Res*., **108**, 2133, doi: 10.1029/2002JB001880.
- Wilson, D., R. Aster, M. West, J. Ni, S. Grand, W. Gao, W.S. Baldridge, S. Semken, and P. Patel (2005), Lithospheric structure of the Rio Grande rift, *Nature*, **433**, 851-855.
- Zhao, D., J. Lei, T. Inoue, A. Yamada, and S.S. Gao (2006), Deep structure and origin of the Baikal rift zone, *Earth Planet. Sci. Lett.*, **243**, 681-691.
- Zorin, Y.A., V.M. Kozhevnikov, M.R. Novoselova, and E.K. Turutanov (1989), Thickness of the lithosphere beneath the Baikal rift zone and adjacent regions, *Tectonophysics*, **168**, 327-337.
- Zorin, Y.A., V.V. Mordvinova, G.L. Kosarev, E.K.Turutanov, B.G. Belichenkoa, and S.S. Gao (2002), Low seismic velocity layers in the Earth's crust of Eastern Siberia (Russia) and Mongolia, Receiver function data and geological implication, *Tectonophysics*, **359**, 307-327.

Discussion

Mon Dec 18th, 2006: Alexei Ivanov
The paper by Liu & Gao is very interesting and, I believe, it will give new impetus to the discussion of the Baikal rift origin. I wish to comment on one sentence from their webpage.

"One possible cause of the low temperature in the MTZ [beneath the rift] is that the opening of the rift at about 35 Ma created a zone of high surface heat flux [*Lysak*, 1984] and partial melt (and consequently reduction in seismic velocity) in the upper mantle beneath the rift."

The authors admit that this is a speculative idea. Indeed, it just cannot be correct. There is no evidence of 35 Ma old volcanism within the rift. The oldest volcanic rocks close to the south Baikal (a few km away from Talaya seismic station used by Liu & Gao) are only 18 Ma old. The oldest rocks in the broader area are not much older (about 22 Ma). I attach a recent paper (Rasskazov et al., 2002), which includes Ar/Ar and K-Ar ages for the South Baikal and Khubsugul lake areas. The puzzle about the Baikal rift is: "Why there is there no volcanism within the deepest rift basins of Lake Baikal?". The same question can be asked regarding a recent paper by Lebedev et al. (Asthenospheric flow and origin of volcanism in the Baikal Rift area, *Earth Planet. Sci. Lett*., **249**, 415-424, 2006.). Any model MUST consider the fact that volcanism seems to be independent of extension in the Baikal rift. There is, however, the influence of pre-existing lithospheric structure on rifting and localization of volcanism.

As for the cold MTZ beneath the Baikal, the easiest solution, in my opinion, is the presence of a Mesozoic slab there. The authors consider this possibility in their paper, but it seems they do not favour it.

last updated 18th December, 2006