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Significant crustal thinning beneath the Baikal rift zone: New constraints from receiver function analysis

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[1] Thinning of the crust of more than 10 km is a major feature of typical continental rifts such as the East African (EAR) and Rio Grande (RGR) rifts. However, numerous previous studies across the Baikal rift zone (BRZ), which has similar surface expressions and tectonic history, and more active seismicity relative to EAR and RGR, have resulted in contradicting amount of thinning, ranging from almost none to more than 10 km. We measure crustal thickness by stacking teleseismic receiver functions beneath 51 sites on the southern and central parts of the BRZ and adjacent Siberian Platform and Sayan-Baikal-Mongolian Foldbelt. Our measurements reveal that beneath the southern part of the Platform, the average crustal thickness is about 38 km, which is about 7 km thinner than that beneath the Foldbelt and the un-rifted part of the BRZ. The thinnest crust, 35 km, is found beneath the central part of the rift, and represents a significant thinning of about 10 km relative to the un-rifted parts of the BRZ. *INDEX TERMS:* 7200 Seismology; 7203 Seismology: Body wave propagation; 7205 Seismology: Continental crust (1242). **Citation:** 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*, L20610, doi:10.1029/2004GL020813.

1. Introduction

[2] Thinning of the crust of more than 10 km has been observed in the Rio Grande [*Wilson et al.*, 2003] and East African [*Prodehl et al.*, 1994] rifts. In spite of numerous geophysical studies, the amplitude and even the existence of crustal thinning beneath the Baikal rift zone (BRZ), which is the seismically most active rift on Earth, still remain as debated issues.

[3] The BRZ (Figure 1) is a 1800 km long system of rift depressions developed during the past 30 million years along the Proterozoic-Paleozoic suture between the Siberian and Amurian microplates [*Keller et al.*, 1995]. It is generally considered as the domal uplift between the Siberian Platform and the Sayan-Baikal-Mongolian Foldbelt [*Logatchev et al.*, 1983]. Like most other major continental rift zones, the BRZ is characterized by higher than normal shallow seismicity, flanking normal faults, higher than normal surface heat flow, and lower than normal mantle velocities [*Zorin and Cordell*, 1991; *Davis*, 1991; *Gao et al.*, 1994a, 2003]. The total horizontal extension across the rift is believed to be between 10 and 20 km [*Zorin and Cordell*, 1991], which implies an average extension rate of 0.3–0.6 mm/yr over the past 30 million years. GPS measurements suggest that the current extension rate across the BRZ is about 10 times of the average rate [*Calais et al.*, 1998; *Suvorov et al.*, 2002].

[4] Previous estimates of the amount of thinning of the crust beneath the BRZ range from less than a few km [*ten Brink and Taylor*, 2002; *Suvorov et al.*, 2002] to more than 10 km [*Logatchev et al.*, 1983]. Most of those results were obtained by using data from experiments that were confined in a particular region (such as the Lake) of the BRZ [*ten Brink and Taylor*, 2002], which makes it difficult for comparing results from other regions; by using refracted data from long seismic refraction profiles, which usually have weak signal from the *Moho* and the resulting crustal thicknesses are essentially averaged values over hundreds of km [*Suvorov et al.*, 2002]; or from inversion of gravity anomalies, which is well-known for its non-uniqueness [*Zorin and Cordell*, 1991]. This paper provides additional constraints on models regarding the structure and dynamics of the BRZ, as well as those regarding the uplift of the Sayan-Baikal-Mongolian Foldbelt, by measuring the crustal thickness (h) through stacking of teleseismic receiver functions, which provide site-specific information on crustal structure.

2. Data

[5] Short-period seismograms collected by the portable Baikal seismic experiment are used in the study. The central frequency for most of the sensors is 1 Hz. The experiment occupied about 60 sites during two field seasons in the summers of 1991 and 1992, along two profiles of about 550 and 1280 km long, respectively. The data set has been used to investigate velocity structure and seismic anisotropy in the mantle beneath the study area [*Gao et al.*, 1994a, 1994b, 1997, 2003]. Broadband seismograms recorded by the two GSN (Global Seismic Network) stations in the study area, TLY (Talya, Russia), and ULN (Ulan Baataar, Mongolia), which are located in blocks 29 and 49 (Figure 1), respectively, are also used. The sampling interval of the seismograms is 0.1 s.

[6] Given the short-period nature of the majority of the seismometers and the main frequency range of teleseismic *P*-wave arrivals, we filtered the seismograms in the 0.1–1.5 Hz frequency band using a four-pole, two-pass Butterworth filter. The filtered seismograms were then visually checked, and those with strong *P*-arrivals on the vertical component were source-normalized by converting them into radial receiver functions using the procedure of *Ammon*

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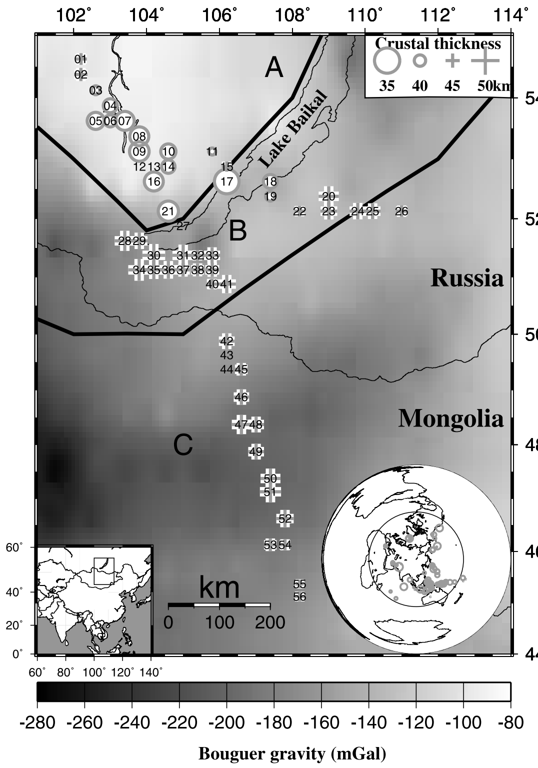

Figure 1. Map showing Bouguer gravity anomalies (data after *Kaban et al.* [1999]) of the study area, the major tectonic regions [*Logatchev et al.*, 1983] (A = Siberian Platform, B = Baikal Rift Zone, and C = Sayan-Baikal-Mongolian Foldbelt), and the locations of the crustal blocks (see the Methods section for the definition of crustal blocks) and resulting crustal thickness variations. The blocks are numbered from the north to the south. The inset at the bottom-right corner shows the location of the events used in the study. The size of a circle is proportional to the number of teleseismic *P*-wave records used from the event. See color version of this figure in the HTML.

et al. [1990]. In the epicentral range 30–95°, a total of 767 high quality radial receiver functions were selected for the portable stations, and about 1000 were selected for the two GSN stations. A clear arrival is found at most of the receiver functions in the time window of 4 to 6 seconds after the *P*-wave (Figure 2).

3. Methods

[7] The horizontal distance between the ray-piercing point with the *Moho* and the recording site is a function of the *P*-wave ray parameter (p). We divide the study area into blocks with a dimension of 0.4° (about 28.0 km) along the EW direction and 0.25° (27.8 km) along the NS direction. We then stack radial receiver functions with ray-piercing points dropping in the same block along the travel-time curves of the converted phases at the *Moho*, *PḿS*, to find the crustal thickness that gives rise to the maximum stacking amplitude [*Dueker and Sheehan*, 1998]. The piercing points are grouped at a depth of 40 km, which is approximately the mean crustal thickness from previous studies.

[8] For a given block, we apply a series of candidate depths h_i in the range from 30 to 55 km at an interval of 0.1 km. For each h_i, we calculate the coordinates of the ray-piercing points by ray-tracing for all the ray-paths. If a piercing point is inside the block, we calculate the difference between the arrival times of *PḿS* and *P* (i.e., the moveout) using [*Dueker and Sheehan*, 1998]

$$t_{ps}^{(i)} = \int_{-h_i}^{0}\left[\sqrt{\left(V_p(z)/\phi\right)^{-2} - p^2} - \sqrt{V_p(z)^{-2} - p^2}\right]dz, \quad (1)$$

where p is the *P*-wave ray parameter, h_i is the depth of the candidate crustal thickness, $V_p(z)$ is the *P*–wave velocity at depth z in a 1D velocity model, and ϕ is the V_p/V_s ratio, which is chosen as 1.75 in this study based on previous measurements in the study area [*Krylov et al.*, 1981].

[9] The receiver functions, which are time series, are then stacked and converted to depth series using

$$A(h_i) = \sum_{k=1}^{n} S_k\left(t_{ps}^{(i)}\right), \quad (2)$$

where n is the number of ray-piercing points in the block, $S_k(t)$ is the amplitude of the point on the kth receiver function at time $t_{ps}^{(i)}$ after the first *P* arrival, and the optimal h for the block is the one that gives the maximum stacking amplitude.

[10] A recent study of mean crustal velocity using deep seismic sounding (DSS) data [*Suvorov et al.*, 2002] suggests that beneath all the blocks in the Platform and the BRZ, the average crustal *P*–wave velocities are between 6.3–

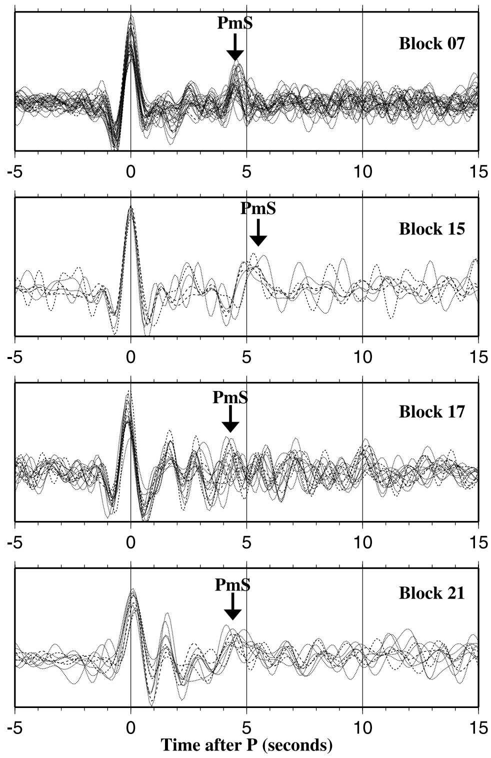

Figure 2. Radial receiver functions used to produce results for four blocks. Apparent shifts of the *PḿS* arrivals relative to each other are mostly caused by the variation in ray parameters. Stacking of the traces after moveout corrections results in coherent depth series (Figure 3).

6.4 km/s. Based on this observation, in this study we assume a constant V_p of 6.35 km/s beneath all the blocks. Obviously, lateral variation in crustal velocity would result in errors in the observed *h*. We estimated that a 5% variation in V_p or V_s leads to a bias of apparent crustal thickness of about 2 km.

4. Results

[11] Crustal thickness is measured beneath a total of 56 blocks with two or more ray-piercing points at 40 km depth (Figures 1 and 3). Results from five of those blocks are excluded from discussions below, mostly due to the lack of an outstanding maxima in the resulting depth series.

[12] We use the bootstrap method [*Press et al.*, 1992] to estimate the standard deviations (STDs) of the optimal *h*. For each bootstrap step, we randomly choose 1-1/*e* = 63% independent receiver functions that belong to a block. About 60% of the chosen ones are then duplicated so that the total number of the new set of receiver functions is the same as that of the original set. Equations (1)–(2) are used on the new set of receiver functions to produce depth series (Figure 3). The resulting *h* measurements for the block are expected to be distributed around the true values [*Press et al.*, 1992]. It turns out that most of the resulting STDs are less than 1 km, which is smaller than the estimated errors associated with possible velocity variations. The small STDs are probably caused by the clear and consistent *PḿS* arrivals on the receiver functions used for the stacking (Figure 2).

[13] The resulting crustal thickness beneath the Platform ranges from 37 to 45 km. In this area the thickest crust is located beneath the northern end of the profile. A gradual northward thickening of the crust with a magnitude of about 7 km is found north of block 5. Our observations are inconsistent with results from inversion of gravity anomalies or DSS studies in this area, which suggested a nearly flat *Moho* with a depth of about 40–42 km [*Pavlenkova*, 1996]. The major feature that was not revealed by either DSS or gravity studies is the relatively thin (about 38 km) crust along the SW margin of the Platform (from blocks 7 to 21).

[14] Within the BRZ, the thickness changes dramatically, ranging from 35 km beneath block 17 to about 48 km at the southern part. The variation is also evident from the original receiver functions (Figure 2). For block 31, the thickness corresponding to the maximum stacking amplitude is about 38 km, which is about 10 km smaller than the neighboring blocks. This could be an artifact given the relatively low number of available receiver functions, and consequently result from this block is not further discussed. Our crustal thickness for block 17 is similar to DSS results obtained in this area (36–37 km [*Krylov*, 1981]), and to gravity results (about 35 km [*Logatchev and Zorin*, 1992]).

[15] The *h* observations beneath the Foldbelt range from 44 to 48 km (Figures 1 and 3), with a mean of 45 ± 1 km. The area is characterized by a broad region of gradual thickening of the crust centered at blocks 50 and 51, with a magnitude of about 4 km. This feature corresponds to systematic variations in surface elevation and Bouguer anomalies (Figure 1). The observed thick crust and the correspondence between *h* and surface elevation suggest that the uplift of the Foldbelt is a recent event, possibly related to the collision between the Indian and Eurasian plates [*Molnar and Tapponnier*, 1975]. The observed thick crust beneath the Foldbelt is inconsistent with the hypothesis that the uplift is the result of a large-scale mantle plume centered at the Hangai dome, which is centered approximately at (100°E, 49°N) [*Windley and Allen*, 1993].

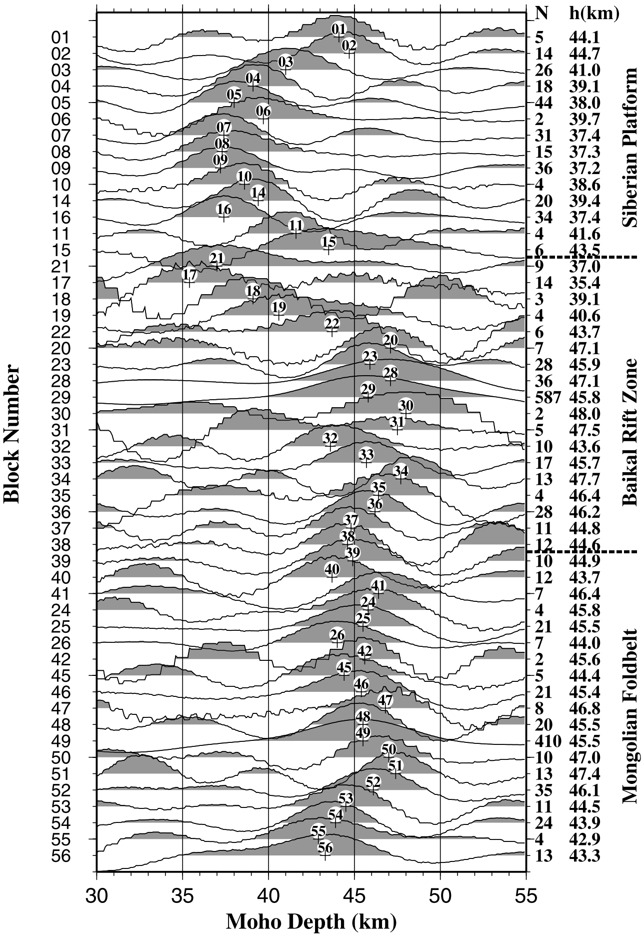

Figure 3. Results from stacking of radial receiver functions. The traces are arranged based on the approximate distance of the blocks from the hypothetical line in the rift with the thinnest crust. The uncertainty in the observations is related to the departure of crustal velocities from those used in the stacking (V_p = 6.35, and V_s = 3.63 km/s), and is estimated to be a few km or less based on previous observations of crustal velocities. Also shown are the number of high-quality receiver functions used in the stacking (N), and the resulting crustal thickness (h).

5. Discussion and Conclusion

[16] Relative to other techniques such as inversion of gravity data, large-aperture seismic refraction, seismic tomography using natural earthquakes, heatflow analysis, and geochemical and geodynamic modeling, the approach used here, i.e., stacking of moveout-corrected receiver functions, is perhaps the most reliable way to obtain crustal thickness beneath the recording sites. While it is generally believed that the crust beneath the BRZ has thinned because

of rifting, the magnitude and consequently the mechanism of the thinning have been issues of debates.

[17] Most previous studies suggested a similar crustal thickness beneath the southern part of the Platform and the Sayan-Baikal-Mongolian Foldbelt [e.g., *Logatchev and Zorin*, 1992]. Our results have confirmed a recent observation [*Zorin et al.*, 2002] showing that on average, the crust beneath the southern portion of the Platform is about 7 km thinner than that beneath the Foldbelt. The crustal thickness beneath the interior part of the Platform, however, is comparable with that beneath the Foldbelt. The amount of crustal thinning beneath the BRZ is thus dependent on the reference region. For instance, the magnitude of the thinning in the study area is insignificant (about 1 km) relative to the southern part of the Platform, but is significant (about 10 km) and is comparable with the other major continental rifts if compared with the interior part of the Platform (blocks 1 and 2) and the Foldbelt.

[18] Beneath the southern part of the BRZ, the observed crustal thickness is similar to that beneath the Foldbelt, implying that thinning of the crust, if exists, is limited in the area occupied by the Lake (Figure 1). Indeed, this area is dominated by left-lateral shearing instead of extension [*Sherman*, 1978]. Thin crust is observed at the central part of the BRZ (blocks 17, 18, and 19). The crustal thickness measurements beneath the Foldbelt adjacent to the central part of the BRZ (blocks 24–26) have similar values as the other part of the Foldbelt and the un-rifted parts of the BRZ. Those observations imply that the pre-rifting crustal thickness beneath the BRZ is similar to that beneath the Foldbelt, i.e., about 45 km, and the amount of thinning observed at central BRZ (about 10 km) represents the actual thinning as a result of the rifting processes. The maximum amount of thinning is found beneath the western edge of the Lake, and the magnitude decreases gradually toward the southeast (10 km at block 17, 6 km at block 18, and 4 km at block 19). The observed large amount of thinning is contradictory to the rifting model proposed by *ten Brink and Taylor* [2002], who suggest that the lower crust beneath the Lake is not significantly rifted.

[19] In summary, our measurements suggest that the amount of crustal thinning beneath the BRZ is at least 10 km, which is comparable with the other major rifts. In the southern part of the BRZ, rifting is limited in the area occupied by the Lake, and in the central part, the amplitude of thinning is the maximum beneath the western edge of the Lake, and reduces gradually toward the southeast.

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