Magma-compensated crustal thinning in continental rift zones

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Continental rift zones are long, narrow tectonic depressions in the Earth's surface where the entire lithosphere has been modified in extension[1]. Rifting can eventually lead to rupture of the continental lithosphere and creation of new oceanic lithosphere or, alternatively, lead to formation of wide sedimentary basins around failed rift zones. Conventional models of rift zones include three characteristic features: surface manifestation as an elongated topographic trough, Moho shallowing due to crustal thinning, and reduced seismic velocity in the uppermost mantle due to decompression melting or heating from the Earth's interior[2–4]. Here we demonstrate that only the surface manifestation is observed at the Baikal rift zone, whereas the crustal and mantle characteristics can be ruled out by a new seismic profile across southern Lake Baikal in Siberia. Instead we observe a localized zone in the lower crust which has exceptionally high seismic velocity and is highly reflective. We suggest that the expected Moho uplift was compensated by magmatic intrusion into the lower crust, producing the observed high-velocity zone. This finding demonstrates a previously unknown role for magmatism in rifting processes with significant implications for estimation of stretching factors and modelling of sedimentary basins around failed rift structures.

The active Baikal rift zone (BRZ, Fig. 1) is located in the centre of the largest continental area on Earth, far from any active plate boundary. Its surface expression is a curved series of 40–80-km-wide graben structures (fault-bounded localized depressions), more than 2,000 km long, at the edge of the Siberian craton. The 660-km-long Lake Baikal in the central part of the rift is the deepest lake on Earth, and contains around 20% of the world's available freshwater resources. The surrounding elevated rift-shoulders reach altitudes of 1,500–2,500 m around the central rift (Lake Baikal is 455 m above sea level), which is similar to other active continental rifts. The BRZ developed during the last ~35 Myr in the Palaeozoic Sayan-Baikal accretionary belt at the late Ordovician-Silurian suture between the Siberian craton and the Amurian plate[5–7].

The development of the BRZ has produced only small volumes of volcanic products, most of which are observed at distances of >100 km from the graben structures[8] (Fig. 1). The total volume of volcanic rocks around the BRZ probably does not exceed 6,000 km³, whereas more than 140,000 km³ of volcanic rocks are estimated around the Kenya rift zone[9]. Weakly alkaline, basaltic volcanism at the BRZ began at around 40–35 Myr ago in the Tunka depression (Fig. 1) and was followed by volcanic pulses, primarily in the surrounding highlands[8].
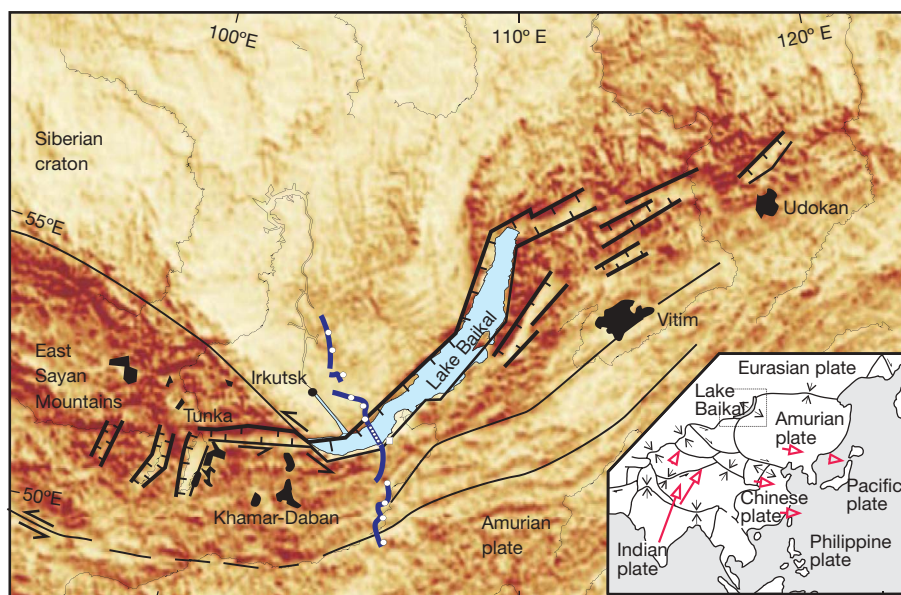

Figure 1 | Shaded relief topographic map and tectonic setting. Main figure, topographic map showing location of seismic profile (blue line) across the Baikal rift zone (BRZ). Seismic sources: large circles, explosions; small circles, airgun line; square, Babushkin supervibrator. Full lines, major tectonic faults; lines with tick marks, normal faults at main grabens[31]; black zones, volcanic provinces[15]. Inset, tectonic setting with the BRZ at the southeastern edge of the Siberian craton (Eurasian plate), modified from ref. 5. Rifting may be caused by eastward escape of terranes due to India–Eurasia collision, extension from Pacific subduction[13], and a possible mantle thermal anomaly[6,10]. Red arrows, GPS measurements of plate motion[32]; black arrows, relative displacement at plate boundaries.

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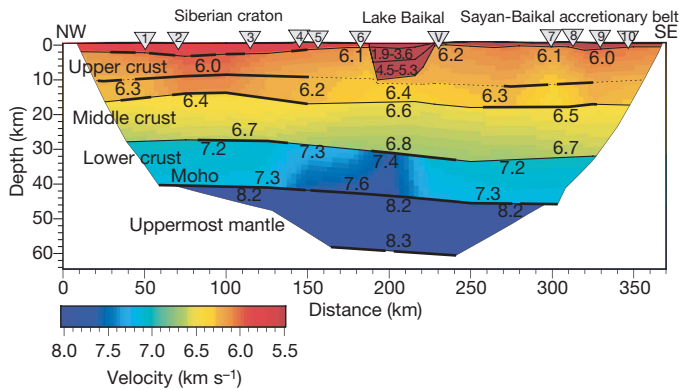
Figure 2 | Model of seismic compressional velocity along the seismic profile across the BRZ. Discontinuities are shown by lines, which are bold at observed reflection points (Methods); seismic velocity is colour-coded (scale at right). The Baikal rift depression is filled with low-velocity sediments (<5.3 km s^{-1}). The crustal thickness is almost uniform and smoothly varying without Moho uplift. The mantle velocity is normal for the Siberian craton, and no low-velocity anomaly is observed to depths of 60 km (Fig. 3). A localized zone in the lower crust exhibits very high seismic velocity ($v > 7.4 \pm 0.2$ km s^{-1}). This zone is strongly reflective (Fig. 3). Triangles with numbers mark shot point locations.

Extension rate in the BRZ has varied over time. Sedimentation rate corresponded to subsidence rate during the early phases of rift formation. It increased during regional uplift around 10–7 Myr ago[7], and

Lake Baikal was probably created by fast subsidence since ~2.5 Myr ago. This sequence has been interpreted in terms of active rifting caused by a mantle plume[6,10], although the rifting was not preceded by significant volcanic activity[8]. Recent interpretation of teleseismic recordings indicates the presence of a narrow thermal anomaly in the mantle, which cannot be shallower than 70 km deep[11,12]. Alternatively, the timing and location of the rifting at Baikal can be explained by passive rifting processes[4] caused by the eastward escape of the Amurian plate (Fig. 1) due to the Himalayan continental collision and plate drag from the subduction of the Pacific plate underneath Asia[13–15].

We present a new seismic velocity model interpreted from a 360-km-long, crustal refraction seismic profile across southern Lake Baikal (Fig. 2), acquired by the Baikal Explosion Seismic Transects (BEST) project (Methods). The model is well constrained by reversed ray coverage along the whole profile. It provides a good fit to 3,290 out of 3,442 observed travel times with a root-mean-square residual of 103 ms, which corresponds to the uncertainty of the travel time picks. The ~10-km-deep and 40-km-wide graben structure underneath Lake Baikal is filled with sediments with seismic velocities (v) of 1.9–5.3 km s^{-1}. The ~10-km-thick sedimentary sequence may be rift-related, although the 4-km-thick lower interval ($v > 4.5$ km s^{-1}) may also consist of pre-rift sedimentary rocks.

The gentle southward crustal thickening from 41 km in the Siberian craton to 46 km (± 1 km) in the Sayan-Baikal accretionary belt implies no Moho uplift, contrary to indications from some low-resolution seismological studies[6,11,16] but in agreement with Deep
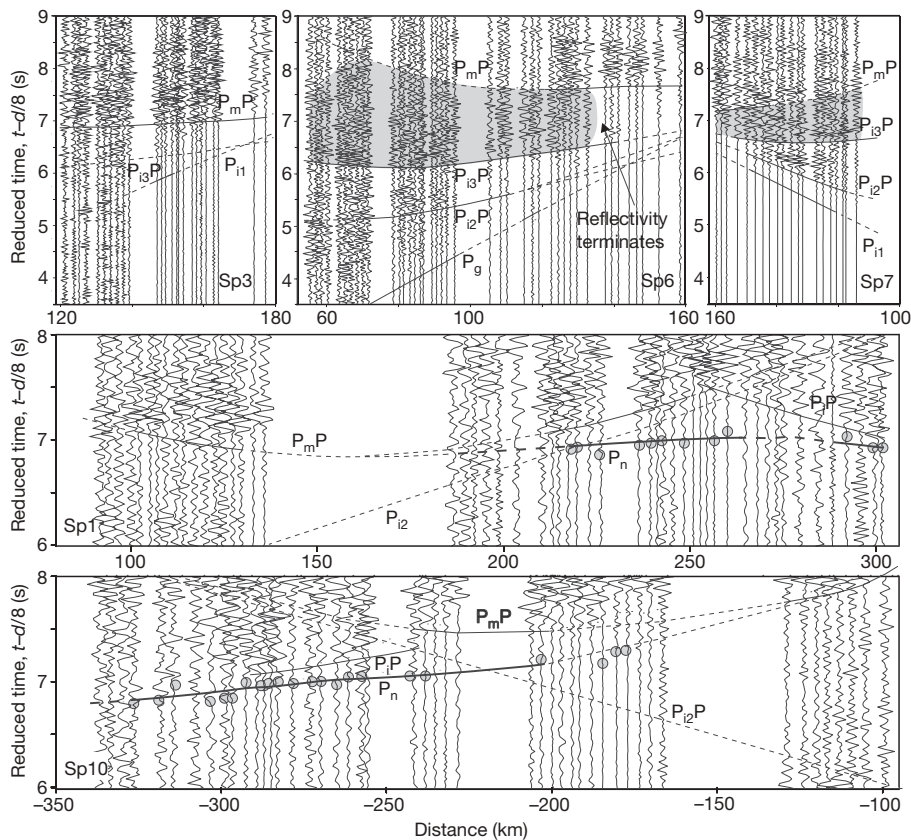

Figure 3 | Seismic sections across southern Lake Baikal with 8.0 km s^{-1} reduction velocity, with superimposed calculated travel times for the model in Fig. 2. The time scale has been reduced by subtracting distance divided by reduction velocity (v_r) from actual time. Full lines are shown where seismic phases are identified, otherwise dashed lines are used. Top left, Sp3 shows reflection from Moho below the rift zone. Lower-crustal reflectivity is modest owing to flat propagation angle (confirmed by full waveform synthetic seismograms). Top middle and right, Sp6 and Sp7 illustrate pronounced lower-crustal reflectivity (grey shading), restricted to

a 50–80-km-wide zone at the BRZ. Terminations (as Sp6 reflectivity at ~130 km offset) constrain location of the reflective bodies to the high-velocity, reflective lower-crustal zone. Middle and bottom, Sp1 and Sp10 are reversed sections, demonstrating that seismic velocities are >8.0 km s^{-1} in the uppermost mantle along the whole profile. Circles show picked travel times. P_g and P_{i1}, crustal refractions; $P_{i2}P$ and $P_{i3}P$, intra-crustal reflections; P_mP, Moho reflection; P_n, refraction from the uppermost mantle; P_lP, reflection from ~60 km depth in the upper mantle (see also Supplementary Information).

Seismic Sounding results[17]. The crust–mantle transition, the Moho, is a reflector, where the velocity increases to $8.2 \pm 0.2 \,\text{km s}^{-1}$ along the whole profile. No sign is observed of low seismic velocity in the uppermost mantle (Fig. 3). These remarkable observations contradict the existing models of rift formation, which predict Moho uplift beneath the rift for the pure shear model[2,6] or outside the rift for the simple shear model[3,14].

The lower crust includes a 50–80-km-wide, high-velocity anomaly 7.4–7.6 (± 0.2) km s^{-1}, beneath and slightly displaced to the northwest of the rift. Significant reverberant reflectivity originates from this zone (Fig. 3). We have modelled this reflectivity with a layered sequence of strong reflectors (layer thicknesses of 400 ± 150 m and large velocity contrasts of around $0.4 \,\text{km s}^{-1}$ (Fig. 4a, Methods), which occupy around 50% of the 13-km-thick lower crust. The very large velocities and velocity contrasts indicate fractionation during cooling of the intrusions[18]. The estimated volume of intrusions ($0.5 \times 13 \times 50$–$80 \,\text{km}$) is equal to the volume of the sedimentary graben structure ($10 \times 40 \,\text{km}$). As such, the presence of the intrusions explains the flat Moho because their volume compensates for the expected crustal thinning around the BRZ. The mass/area of vertical columns ($1.49 \times 10^8 \,\text{g m}^{-2}$ to 50 km depth) is constant to within $\sim 1\%$ along the profile, as calculated for densities derived from the seismic velocity model. Hence, isostatic equilibrium of the crust is maintained as the low density of the sediments is compensated by the high density of the intrusions.

Seismic and gravity results[19] from the Palaeozoic Dniepr-Donetsk rift zone in Ukraine also show a flat Moho and reflectivity indicative of mafic intrusions in the lower crust with thicknesses similar to the BRZ. The Kenya rift also shows less Moho uplift than expected from the observed amount of stretching, which has been explained by the presence of intrusions with thicknesses of 200–500 m (ref. 18). The average velocities in the lower crust and uppermost mantle are lower below the Kenya rift than the BRZ, which may be due to high temperatures[20]. Reverberative seismic reflectivity below the rift zones may be caused by intermixed layering of primarily olivine- and pyroxene-rich rocks with layers of plagioclase-rich components. Numerical simulation shows that mafic intrusion into a cold crust will take the form of sills[21], in accordance with our observations.

Contrary to other active continental rift zones[1,22–24], there is no change in seismic velocity in the uppermost mantle beneath the BRZ. Hence, no thermal anomaly from the uppermost mantle has reached the base of the crust at the BRZ. Our results show that any low-velocity anomaly in the mantle must be located deeper than a distinct seismic reflector at 60 ± 5 km depth (Fig. 2), thus supporting a recent teleseismic determination of a >70-km-deep asthenosphere[11].

Our new results have implications for estimation of stretching factors for rift zones. The β-factor (the ratio between initial and final thickness of the crust) based on the total crustal thickness is 1.3, whereas it is 1.7 if the lower-crustal intrusions are taken into account (Fig. 4b). The β-factor and the local heating of the crust by intrusions are important parameters for modelling basin evolution and possible hydrocarbon formation around failed rift zones. A β-factor of 1.7 will lead to decompression melting of the mantle for a 100-km-thick lithosphere[25]. The present lithospheric thickness of 60–70 km (ref. 11) implies a similar stretching factor, which together with a slightly elevated geotherm[20] explains the melting. Petrologic studies indicate a slightly elevated mantle temperature at the depth of melting[15] and BRZ magmatism is similar to regional magmatism[26]. Hence a mantle thermal anomaly may be present but has not yet reached the surface[7].

The seismic velocities in the lower-crustal anomaly are higher than often observed at underplated continental margins. Some of the highest velocities observed at the North Atlantic margins[27,28] are in the interval 7.2–7.7 km s^{-1}, which corresponds to 7.4–7.9 km s^{-1} at conditions in the BRZ lower crust (40 km depth and 400 °C temperature for[29] $dv/dp = 0.0002 \,\text{km s}^{-1}\,\text{MPa}^{-1}$ and $dv/dT = -0.0004 \,\text{km s}^{-1}\,{}^{\circ}\text{C}^{-1}$, where p and v are respectively pressure and temperature). Theoretical velocities of oceanic crust[28,29] are 7.2–7.6 km s^{-1} at BRZ conditions, slightly less than our observation. However, these predicted velocities may be underestimated for the BRZ because (1) the magma originates from a depleted continental mantle[15], (2) the magma may have fractionated during solidification[18], and (3) it solidified in a cold crust[20] at conditions favourable for metamorphism of gabbro into eclogitic rocks with a seismic velocity of 7.8–8.0 km s^{-1} at a depth of 40 km, depending on the chemical composition[30]. Structural anisotropy due to layering of the intrusions will bias our observations towards the highest velocity instead of the average velocity, because the velocity observation is primarily based on horizontally travelling waves. Although very high, the observed velocity is within predicted values from laboratory measurements on mantle-derived magmatic rocks.

High-velocity lower crust has been earlier observed in a seismic profile along the strike of the BRZ and interpreted as normal cratonic lower crust with indication for simple shear deformation, where the top of the lower crust of the Siberian craton transforms the extension eastward to beneath the Mongolian plateau (Fig. 4c)[14]. In contrast, our new results with anomalously high velocity in a lower-crustal zone almost directly below the rift indicate instead mainly pure shear deformation (Fig. 4a). The intrusions may have formed during the slow rift phase (10–2.5 Myr ago).

The surface manifestation of the BRZ is typical for rift zones, but the seismic structure of the crust and uppermost mantle rules out the two other characteristic features of continental rift zones. Neither Moho uplift nor any low-velocity anomaly in the uppermost mantle are inferred from the new controlled source seismic profile across
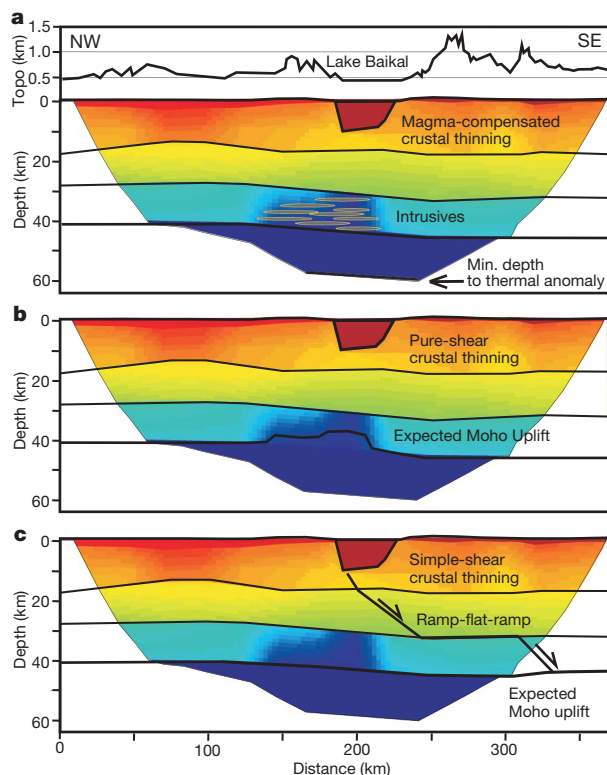
Figure 4 | Three models for formation of the BRZ superimposed on the seismic velocity model. a, Our preferred model in terms of magma-compensated crustal thinning: the high-velocity, reflective zone in the lower crust includes 50% of intrusive material, which explains the flat Moho. The deepest reflector indicates the minimum depth to the asthenosphere (or significant positive thermal anomaly).Topography is shown at top. **b,** Pure shear[2,4] predicts uplift of Moho below the BRZ (drawn as expected uplift without intrusions based on actual lower-crustal velocity), which is not observed in the seismic model. **c,** Simple shear[3] predicts uplift of Moho (here drawn according to ref. 14) outside the BRZ, which is not observed to a distance of 200 km. Moreover, this model does not explain the reflective zone in the lower crust with abnormally high seismic velocity.

southern Lake Baikal. These results indicate that no mantle thermal anomaly has reached close to the base of the crust, and that the rifting processes are not driven by a mantle plume. Significant volume of magmatic intrusions, balancing the expected crustal thinning, explains the apparent lack of crustal thinning beneath the BRZ.

METHODS SUMMARY

The seismic model is interpreted from data acquired by the Baikal Explosion Seismic Transects (BEST) project, which is a collaboration between the University of Copenhagen, the Siberian Branch of the Russian Academy of Sciences, and the Polish Academy of Sciences. BEST applied state-of-the-art refraction methods along the 360-km-long profile across southern Lake Baikal. Seismic sources included 10 chemical explosions in 50-m-deep boreholes (500–2,500 kg of TNT), 234 air gun shots (total volume 60 l) in Lake Baikal, and 6 vibration sweeps (5.8—9.7 Hz over 45 min) by the stationary Babushkin super-vibrator (100 ton weight). Seismic data were recorded by 175 Texan seismographs with 4.5 Hz vertical geophones. High quality signals are correlated along the whole profile with ±100 ms uncertainty (±300 ms for the supervibrator).

Data were interpreted by ray tracing in two-dimensional models of seismic velocity versus depth including discontinuities. Trial-and-error modelling (top-down approach) is based on observed travel times of refracted and reflected signals from the crust and uppermost mantle, followed by automatic inversion for selected parameters. Initial forward modelling is necessary because of the inherent nonlinearity of wave propagation. The model provides a good fit to 3,290 out of 3,442 observed travel times with root-mean-square residual travel times of 103 ms, which corresponds to the uncertainty of the picks. Ray-tracing synthetic seismograms improved the constraints on velocity gradients.

Strong, reverberating seismic reflectivity from a lower-crustal zone has been modelled by full waveform calculation of synthetic seismograms. The reflectivity method for one-dimensional models constrains average layer thicknesses to 400 ± 150 m and 0.4 km s^{-1} velocity contrasts. Calculations with the Tesseral program for two-dimensional models confirm reflectivity results and constrain the lateral extent of the reflective zone to coincide with the high-velocity zone in the lower crust below the BRZ (see also Supplementary Information).

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