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A broken plate beneath the North Baikal rift zone revealed by gravity modelling

E. B. Burov*, F. Houdry², M. Diament¹, J. Déverchère²

Abstract. We modelled a 1200 km long gravimetric profile in the North Baikal rift to assess the mechanical behaviour of the lithosphere, using a numerical model that accounts for realistic brittle-elastic-ductile rheology. We used published seismicity and refraction data, a new 5°x7.5° free-air/Bouguer gravity and topography data set, and a detailed map of faults obtained from high resolution SPOT imagery. Analysis of the gravity field over the North Baikal rift zone indicates significant asymmetry of the mechanical processes governing the deformation of the diverging sides of the rift. These anomalies cannot be explained by a conventional continuous plate undergoing extension beneath the rift zone, whereas a strong mechanical discontinuity (wedge shaped detachment zone beneath the rift axis) is able to reproduce observations. Such a discontinuous model provides a good fit to the gravity and crustal thickness data and explains the deep seismicity reported there.

Introduction

Among the present-day continental rift systems, the Baikal rift zone (BRZ) is believed to represent an archetypal rift in the initial stages of continental plate divergence. This conventional rifting model mainly implies thinning of the crust and negligible lithospheric strength, at least in the vicinity of the rift axis, on the basis of high heat flow and intense normal faulting throughout the upper crust. However, recent studies based on depth distribution of earthquakes, flank uplift patterns, and gravity anomalies over the East African rifts [Shudofsky et al., 1987; Ebinger et al., 1989], the Rio Grande rift [Olsen et al., 1987], or BRZ [Diament and Kogan, 1990; Déverchère et al., 1991; Ruppel et al., 1993] provide evidence for a high mechanical strength within the lithosphere subject to extension. Analytical and numerical models confirm that plate flexure must be considered in this context to explain uplifted rift flanks that rise over 1 km above the surrounding topography [e.g., Weissel and Karner, 1989; Chéry et al., 1992]. In the eastern BRZ, hypocenter relocations show widespread and unusual seismic deformation throughout the upper 30 km of the crust [Déverchère et al., 1993], in a region where interpretation of seismic refraction and reflection data indicate a thicker crust (40-44 km) than in the southern rift (35-39 km) or in the surrounding stable zones (around 40 km) [Puzyrev et al., 1978; Zorin et al., 1989; Logatchev and Zorin, 1992]. In addition to the absence of crustal thinning, it was also suggested [e.g., Ruppel, 1992], that significant effective elastic thickness (Te) of the lithosphere (~50 km, [Ruppel et al., 1993]), low heat flow, deep seismicity (hypocenters as deep as 60 km, [Déverchère et al., 1991, 1993]), and, finally, an absence of volcanic activity (Figure 1) suggest that the North Baikal rift (NBR) is rather atypical. In this paper, we analyse the short wavelength gravity field in order to investigate the crustal thickness variations and mechanical lithospheric properties beneath the NBR. This is done through the study of density contrasts associated with the Moho and modelling of the mechanical behaviour of the lithosphere along representative profiles (Figures 1, 2). We focus on the north-eastern rift, where the surface expression of extension is clear, earthquake distribution related to major faults is constrained with high accuracy (22 km, [Déverchère et al., 1993]), surface geology is known [Houdry et al., 1993], as are the depth and geometry of the sedimentary basins [Logatchev and Zorin, 1992]. The sedimentary basins are clearly distributed in an en-échelon pattern over a broad area (about 300 km) where the Protérozoic and Paleozoic granitoids are more homogeneous, than across the Central and Southern BRZ located on the suture zone between the Siberian platform and the folded mountain ranges of Caledonian Sayan-Baikal belt (Figure 1). This area is presently dominated by N160° extension [Doser, 1991; Déverchère et al., 1993] that could have been preceded by an about N115° extension [Houdry et al., 1993]. The latter would have favoured a strike-slip component along the major border faults.

Gravity field analysis and Mechanical Modelling

We used the topography and gravity data set provided by the International Scientific Environmental Centre of Russian Academy of Sciences (ISEC). It consists of 5°x7.5° free air (FAA) and complete Bouguer gravity anomaly (BA) grids, including terrain corrections (within 200 km of gravity stations), and corresponding elevations (Figure 2). The resolution of the original point data is reported to be around 1'x1', the accuracy of FAA is about 2-4 mGal [M. Kogan, pers. comm.]. The digital topography was checked with the ONC topography (Operational Navigational Charts, Defence Mapping Agency) and showed a good agreement in the study area (Figure 3). To separate the lithospheric and deep sub-lithospheric sources of the observed gravity anomaly, we computed a sum of 10 first harmonics of the gravity field (GRIM-3L1 global field model [Reigber et al., 1985]). This long wavelength component appears to provide only a slight negligible EW trend of 0.5-1 mGal per 100 km (Figure 3). To constrain the sediment thickness in the basins, the faults geometry and the crustal thickness, we used topographic cross-sections combined with geophysical data from Puzyrev et al. [1978], Zorin et al. [1989], Krylov et al. [1990], Logatchev and Zorin [1992] and Déverchère et al. [1993]. The original complete BA, provided by ISEC, adopts crustal density of 2300 kg/m³. Using the original FAA, we extracted the terrain corrections from the old complete BA and recomputed BA for more realistic value of 2670 kg/m³ (Figure 2). To account for surficial density variations, we also corrected BA over the sedimentary basins for the effect of sedimentary fill, assuming density of sediments ρ=2400 kg/m³. This correction does not exceed 10-15 mGal. We did not account for the dense batholith inclusions reported on the north side of the rift [Yu. Zorin, pers. commun.], due to the absence of data on their exact location, depth and geometry.

The linear shape of the gravity anomaly in the northeast direction (direction of the rift axis, Figures 1, 2) advocates for 2D analysis. We compiled data along seven 1200 km profiles in the direction of the present day extension (roughly perpendicular to the major structures of the axial Upper Angara basin, Figures 1, 2). A 800 km segment of the most representative profile A'-A is shown in Figure 3. Analysis of the Bouguer gravity profiles reveals significant deviations from the local (Airy) isostatic equilibrium model (Figure 3). The major signature of the deviations is the positive anomaly of about 40-50 mGal observed 100-150 km to the north-west of the rift axis (Upper Angara basin) and the asymmetric negative anomaly observed 150-200 km to the south of the rift axis (Tispa-Baunt Basin). The topography far to the north of the Upper Angara Basin is too low and flat to trace out any significant difference between local and regional compensation.
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90°E 100°E 110°E 120°E 130°E
50°N

Fig. 1. Geological context of the Baikal rift zone (simplified from the Geological World Atlas, UNESCO, 1976). The line (A-A') is a 800 km part of the representative gravimetric profile used for this study (Figures 2, 3 and 4). White arrows are the directions of extension obtained from stress tensor analysis (for the northern part of the rift, Dévérchère et al. [1991; 1993]; for the middle part of the rift, Doser [1991]). Thin black arrows are the direction of fault movement from geological observations, including field scarp measurements and SPOT imagery analysis [Houdry et al., 1993].

To explain BA over the rift, we first tried several traditional continuous plate models of regional (flexural) compensation of the topography. We began from the simple flexural models based on elastic plate approximation and end with more realistic plasto-
elasto-viscous (brittle-elasto-ductile) rheology models, implying experimental rock mechanics data [Burov and Diamant, 1992]. The latter models use the Byerlee law of brittle failure for the uppermost crust and mantle, and power law creep within the ductile domains [Kirby, 1987] (\( \varepsilon = A \exp(-H^*/RT) (\sigma_1 - \sigma_3)^n \)), where \( \varepsilon \) is the strain rate; \( A \) is a material constant, \( A = 5.6 \times 10^6 \) and \( 4.8 \times 10^6 \) MPa\(^{-sec}\) for quartz (upper crust) and olivine (mantle), respectively; \( H^* \) is the activation enthalpy, \( H^* = 0.19 \times 10^6 \) J mol\(^{-1}\) for quartz and \( 0.533 \times 10^6 \) J mol\(^{-1}\) for olivine; \( R \) =8.3144 J mol\(^{-1}\) K\(^{-1}\) is the gas constant; \( T \) [K] is the temperature; \( n=3 \) for quartz and 3.5 for olivine [Kirby, 1987]; \( \sigma_1, \sigma_2, \sigma_3 \) are the principal stresses. The condition of the brittle failure is: \( \sigma_1 = (\sigma_1 - \sigma_3)/3.9 \) if \( \sigma_3 < 120 \) MPa, and \( \sigma_1 = (\sigma_1 - \sigma_3)/2.1 \) if \( \sigma_3 > 120 \) MPa [Byerlee, 1978].

As compared to the other continental rift zones, the average \( T_e \) for the BRZ is relatively high (~50 km, [Ruppel et al., 1993]), but it is much lower than the maximum mechanical thickness of 80-100 km that could be expected for a lithosphere of this age (400 to 700 Ma, [Logatchev and Zorin, 1992]). This upper strength limit implies a strong lower crust dominated by rocks with high temperature of creep activation (\( b \)) (e.g. diabase, [Burov et al., 1993]). On the contrary, the observed low \( T_e \) (~50 km) suggests that the lithospheric thickness is reduced by decoupling of the strong upper-

![Fig. 2. The BRZ: 5'x7.5' Free Air (FAA) and complete Bouguer gravity anomaly data with location of 7 data profiles running across the NBR. The contour interval is 20 mgal. The grey shade interval is 10 mgal. The shade scale for BA is to be shifted by -90 mgal as compared to that for FAA.](image)

![Fig. 3. The profile A-A'. Top: observed FAA, BA and theoretical BA for continuous brittle-elasto-ductile plate models. Observed gravity anomalies: circles are the FAA; triangles are the BA; dashed line is the first 10 harmonics of the gravity field. Curve "\( T_e=50 \) km" is the theoretical BA for a plate with a weak decoupled lower crust and no horizontal extension (summary strength, in terms of \( T_e \), is ~50 km). Curve "\( T_e=100 \) km" is for the same model, but with a strong coupled lower crust. Curve 1 is a theoretical BA for a plate subjected to extension and flexure. Middle: topography and the interpretative fault geometries. Bottom: rheological structure of the extended plate. White areas are competent quasi-elastic zones. Grey areas are domains subjected to non-elastic deformation (brittle or ductile failure). Black areas are zones of additional non-elastic failure due to flexure. The uppermost mantle remains quasi-elastic and is free of plastic deformation, the crust and the lower mantle lithosphere undergo significant non-elastic strain.](image)
crust from the uppermost mantle by a weak (low $\theta_k$) lower crust [Burov et al., 1993]. Therefore we chose low $\theta_k$ rheology (e.g. quartz) for the whole crust. This choice is partly validated by the presence of an intracrustal low velocity zone in the BRZ [Puzyrev, 1981], which might be associated with the weak lower crust.

A 2-D finite difference model accounting for the plasto-elasto-viscous behaviour of the continental lithosphere was used to study geologically realistic scenarios of plate deformation. The evolution of the system is governed by mass, momentum and energy conservation equations [e.g., Bassi, 1991; Chéry et al.; 1992]:

$$\rho \frac{\partial \varepsilon}{\partial t} + \nabla \cdot (\varepsilon \mathbf{v}) = \rho g + \nabla \cdot \mathbf{T}$$

and

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (\varepsilon \mathbf{v} T) = H_r + H_d$$

where $\rho$, $\varepsilon$ are the initial and current densities, $G$ is the gradient of deformation, $g$ is the gravity acceleration, $\sigma$ is the stress tensor, $C_p$ is the specific heat ($\rho C_p = 3 \times 10^6, 4 \times 10^7$ J/(m$^3$K)$^{-1}$) for the upper, middle and lower crust, and $H_r$ and $H_d$ are the radiogenic and dissipative heat production per unit volume [Burov et al., 1993]. To achieve rapid convergence of the non-linear finite difference algorithm, we use a semi-analytical non-elastic plate approximation [Burov and Dietrich, 1992] for the predictor/corrector scheme, controlling the effective bending moment $M_{eff}$, the longitudinal ($T_{xx}$) and the vertical shearing ($Q_{xy}$) force components per unit width of the plate:

$$M_{xx} = -\frac{\partial \sigma_{xx}}{\partial y} (y - y_i) dy; \quad T_{xx} = -\frac{\partial \sigma_{xx}}{\partial y} dy; \quad Q_{xy} = -\frac{1}{2} \sigma_{xy} dy$$

($y_i$ is the depth to the $i$th neutral plane). The starting temperature distribution and yield-stress profiles were obtained from the solution of the heat transfer problem for the continental lithosphere [Burov et al., 1993], assuming thermal age of 400 Ma and $\varepsilon = 1 \pm 3 \times 10^{13}$ sec$^{-1}$ [Ruppel, 1992; Houdry et al., 1993]. Initialisation of necking requires an initial localised strength defect. Such defect was inferred beneath the axial Upper Angara basin (major depressed zone). We use information on the geometry and location of normal faults, deduced from high resolution SPOT imagery, field measurements [Houdry et al., 1993] and seismicity data [Dénervêtre et al., 1993] to consider fault-induced stresses.

**Results and Discussion**

The general result of these analyses is to show that continuous plate models of lithospheric extension fail to reproduce the observed gravity anomalies (Figure 3). Models of lithospheric flexure without extension produce BA that do not differ enough from the Airy anomaly (Figure 3). Models of extension with flexure [e.g., Chéry et al., 1992], that results in a crustal/mantle necking beneath the rift axis and consequent flexural uplift of the rift shoulders, oblique to the direction of the present-day extension, obtained from stress tensor analysis [Dénervêtre et al., 1991] (Figure 1). The continuous extension produces a positive FA (exception) that fits the observations. The upward bending of the northern rift side leads to an increase in the extensional defor-
deviatoric stresses in the uppermost crust and mantle, and therefore decreases the limits of the brittle failure. This could explain the asymmetry in the seismicity and fault distributions on opposite sides of the NBR (Figure 3 and 4). The geometry of the detached area roughly coincides with the geometry of a system of normal faults that bound the basin and penetrate the lower crust at depths up to 30 km [Devêrèchère et al., 1993]. This area could be caused by tearing off of the rift neck during extension, e.g. by the past ESE/WNW strike-slip movement, oblique to the direction of divergence (the strike-slip component is now minor, probably resulting from the Asia-India collision [Tapponnier and Molnar, 1989]).

Conclusions

The analysis of the short wavelength gravity field in the light of seismological and geological data suggests that the NBR presents a quite untypical “broken” or “cracked” rift. We believe that the present behaviour of the diverging plates in the NBR is not associated with conventional rifting by stretching of the continuous lithosphere, but requires a mechanical discontinuity (block-like detachment) beneath the rift axis. Due to this detachment zone (its existence is confirmed by the past strike-slip faulting, supposedly resulting from the Asia-India collision [Tapponnier and Molnar, 1979]), the mechanical interaction between the sides of the rift is minor in the direction of divergence, resulting in that the lithospheric deformation is well explained by the flexural uplift/descent of the both detached sides of the rift.

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