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Crustal deformation in the Baikal rift from GPS measurements

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Abstract. Three years and four campaigns of Global Positioning System (GPS) measurements (1994-1997) in the Baikal rift zone, largest active continental rift system in Eurasia, show crustal extension at a rate of 4.5±1.2 mm/yr in a WNW-ESE direction. A comparison with moment release of large historical earthquakes suggests that elastic strain is currently accumulating in the Baikal rift zone along active faults that currently have the potential for a M=7.5 earthquake. The GPS-derived extension rate in the Baikal rift zone is at least two times greater than the prediction of most deformation models of Asia. This result could reflect the dynamic contribution of the Pacific-Eurasia subduction to intracontinental deformation in Asia, in addition to the effect of the India-Eurasia collision.

Introduction

The Baikal rift zone, located at the northern edge of the central Asia intracontinental deformation zone (Figure 1), is the largest active continental rift system in Eurasia (Tapponnier and Molnar, 1979). It extends over a distance of about 2000 km along the S-shaped paleozoic suture that separates the Siberian Platform from the Sayan-Baikal mobile belt (Logatchev and Zorin, 1992). We present the results of four campaigns of Global Positioning System (GPS) measurements in the southern and western parts of the Baikal rift zone. This data set provides the first direct measurements of the current displacement rates at the boundary between stable Eurasia and East China.

GPS Measurements and Data Processing

GPS measurements in the Baikal rift zone were initiated in July 1994 with the installation and first observation of a network of 11 sites covering its southern and western parts (Figure 1). The sites IRKU and ULAN were reoccupied in August 1995. The whole network was remeasured in August 1996 and August 1997. We used Ashtech P12 and Z12 GPS receivers sampling at 30 seconds. Each site was surveyed 22 hours a day for an average of four consecutive days during each campaign. We benefit, since 1996, from the data from the Irkutsk permanent IGS station (IRKT), located 40 m away from the IRKU mark.

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We processed pseudorange and phase data in single-day solutions using the GAMIT software (version 9.6, King and Bock, 1997). We solved for regional station coordinates, satellite state vectors, 13 tropospheric zenith delay parameters per site and day, and phase ambiguities using doubly-differenced GPS phase measurements. We used IGS final orbits, IERS earth orientation parameters, and applied azimuth and elevation dependant antenna phase center models, following the tables recommended by the IGS. Four primary and eight secondary IGS stations (ONSA, GRAZ, TIDB, FAIR, HART, KOKB, TSKB, USUD, TAIW, KITA, SHAO, IRKT) were included in the processing to serve as ties with the International Terrestrial Reference Frame 1994 (ITRF94, Boucher et al., 1996).

The least squares adjustment vector and its corresponding variance-covariance matrix for station positions and orbital elements estimated for each independent daily solution were then passed to a Kalman filter (GLOBK, Herring et al., 1990) in order

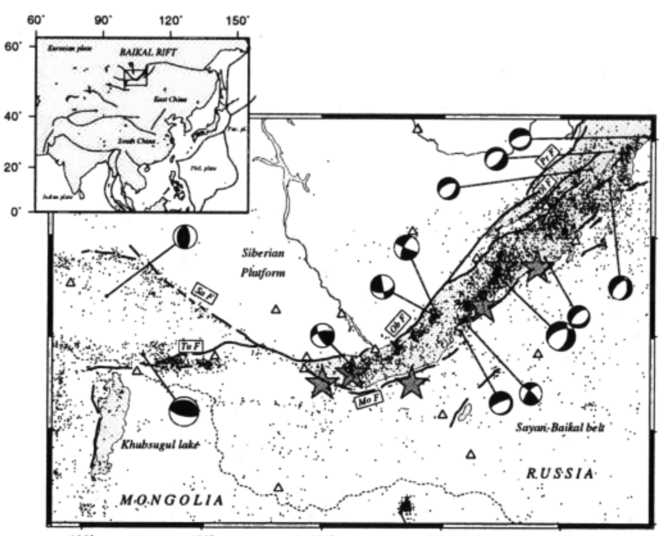

Figure 1. Tectonic setting of the southern Baikal rift zone: major active faults (Sa F: Sayan fault, Tu F: Tunka fault, Mo F: Morskoy fault, Ob F: Obruchevsky fault, Ol F: Olkhonsky fault, Pr F: Primorsky fault), instrumental seismicity (dots, 1962-1980, M>2.8), historical earthquakes (stars, see Table 2), and focal mechanisms of major earthquakes. The triangles indicate the location of the GPS sites.

Table 1. Velocities (V, mm/yr) with respect to IRKU and associated one standard deviation formal errors (σ, mm/yr) computed by scaling the 1-σ uncertainties of the final adjustment by the overall chi-squared per degree of freedom.

Lon.	Lat.	Vlon	Vlat	σlon	σlat	correlation	Site code
108.24	52.97	3.9	1.1	1.4	1.0	-0.0323	TURK
107.62	51.81	2.8	-4.0	1.0	0.6	-0.0693	ULAN
106.58	52.79	-0.7	2.2	1.2	1.0	-0.0430	ANGA
106.49	50.74	3.5	0.2	1.2	1.0	-0.0549	KIAT
106.01	51.17	4.6	-0.8	1.2	1.0	-0.0596	UDUN
105.50	53.06	0.5	0.5	1.2	1.0	-0.0629	BAYA
104.89	51.85	2.2	-0.5	1.4	1.2	-0.0975	LIST
104.32	52.22	0.2	0.4	1.4	1.2	-0.0589	IRKT
104.32	52.22	0.0	0.0	1.0	0.6	-0.0777	IRKU
103.74	51.77	2.3	0.2	1.2	1.0	-0.0517	KULT
103.70	51.65	1.6	0.0	1.4	1.0	-0.0376	SLYU
102.21	51.76	0.1	-2.3	1.4	1.0	-0.0460	BADA

to estimate station positions and velocities. We imposed the reference frame by minimizing the position and velocity deviations of IGS core stations with respect to the ITRF94 while estimating an orientation, translation and scale transformation. The height coordinate and velocity were downweigthed by a factor of 10 relative to the horizontal components.

Velocity Field

Our results over the three year period 1994-1997 are listed on Table 1 and displayed in Figure 2. The formal errors have been computed by scaling the 1–σ uncertainties of the final adjustment by the overall chi-squared per degree of freedom. The uncertainties in the horizontal components of the velocity estimates range between 0.6 and 1.4 mm/yr (1–σ). Long term baseline repeatabilities (weigthed RMS scatter about the best fit linear regression to the position time series) are on the order of 2 to 3 mm for the horizontal components and 5 to 10 mm for the vertical component (Figure 3). The GPS-derived velocity field (Figure 2) shows that:

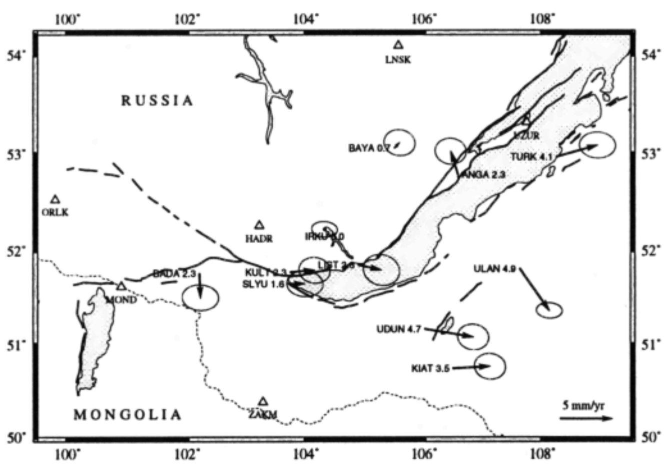

Figure 2. Velocities obtained from GPS measurements in the central and southern parts of the Baikal rift and the Tunka basin. The arrow length is proportional to the displacement rate, indicated in mm/yr next to the site code name. The velocities are expressed relative to IRKU. The ellipses represent 95% confidence intervals.

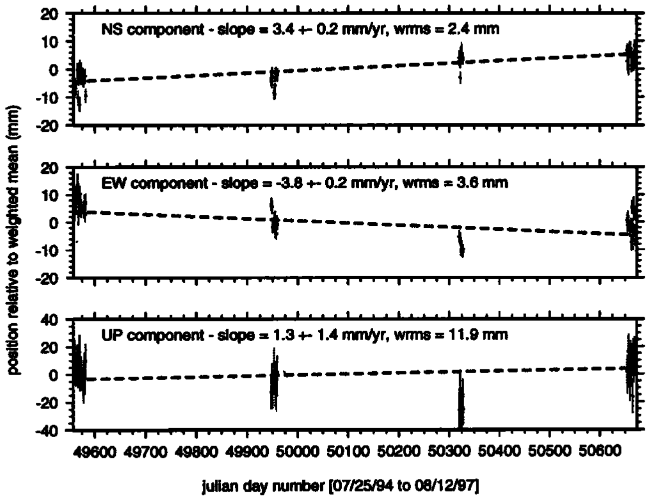

Figure 3. Baseline time series between Irkutsk and Ulan Ude. Each point represents a daily solution with its 1–σ error bar. The four sets of point represent the 94, 95, 96, and 97 measurements. The dashed line is the best fit linear regression computed from a weighted least squares adjustment to the data.

1. The two sites located on the stable Siberian platform (IRKU, BAYA) show no relative motion at the 1 mm/yr level. This result is a good internal test of the overall quality of the velocity field, since both sites are located on the same aseismic and undeformed crustal block with no known active fault between them.
2. The four sites located on the southeastern side of the rift (UDUN, KIAT, ULAN, TURK) show extension across the rift zone at an average rate of 4.5±1.2 mm/yr (1–σ). This result is in good agreement with geological estimates based on topographic offsets in holocene alluvial fans that indicate 5 mm/yr of total extension in the northern part of the Baikal rift zone during the last 10,000 years (Houdry, 1994). The direction of extension varies between N80 and N140 (relative to IRKU). Given the small number of observation epochs available, it is not possible to determine whether this variability of tectonic origin or if it reflects GPS measurement errors. The direction of extension appears to be oblique to the direction of the major normal faults, implying left-lateral wrench-extensional faulting in the southern part of the Baikal rift zone. This result is consistent with earthquake focal mechanisms (Figure 1), stress tensor calculations, and microtectonic measurements in the southern Baikal rift zone that predict slip vectors trending N105 on the major active faults (Petit et al., 1996; Delvaux et al., 1997).
3. The five sites located along the major active fault zone that bounds lake Baikal to the northwest and continues westward along the northern side of the Tunka basin (BADA, SLYU, KULT, LIST, ANGA) show velocities on the order of 2 mm/yr relative to IRKU. All these sites are located in the close vicinity of a major active fault and are therefore likely to reflect elastic strain accumulation.
4. We observe no significant relative motion (at the 1 mm/yr level) between KULT and SLYU, located 10 km from each other on each side of the Sayan-south Baikal active fault. This probably indicates that the Sayan-south Baikal fault is currently locked.

Discussion

Comparison with Seismic Moment Release

According to the historical seismicity catalogs of Solonenko (1977) and Kondorskaya and Shebalin (1982), six earthquakes exceeding $M=6^{1/4}$ have occurred in the south Baikal rift since 1700 (Table 2). Three events most probably occured on the Obruchevsky fault, that bounds the Southern Baikal basin to the north, whereas the other three occured in the Central Baikal basin along the Morskoy fault (Figure 1). Following the empirical magnitude-moment law given by Hanks and Kanamori (1979), these two subsets released minimum seismic moments of 4.8×10^{20} Nm and 2.2×10^{20} Nm, respectively. In spite of large uncertainties due to crude estimates of seismic moments for the period 1700-1900, these values are comparable to the 0.9 to 2.6×10^{20} Nm seismic moment release over the last 85 years proposed from long-term and short-term kinematic deformation models of Asia (Holt et al., 1995).

In order to convert this cumulated seismic moment release into total slip on each fault, and since active faults in the southern and central Baikal basins are well delineated, we use the approach proposed by Brune (1968). Using a seismogenic thickness of 25 km (Déverchère et al., 1993), the fault dip angles given in Table 2, and a rigidity of 3.3×10^{11} dyn/cm^2, we find a cumulated slip of 3.3 m along the South Baikal fault and 1.0 m on the central Baikal fault, corresponding to average horizontal slip rates of 5.6 mm/yr and 2.1 mm/yr respectively. These rates, that reflect seismic moment released over 3 centuries, are comparable to the 4.5 mm/yr far-field extension rate across the rift obtained from GPS measurements over 3 years. This result, together with GPS results showing that the Sayan-south Baikal fault is locked, suggests that little or no aseismic slip is occurring along active faults in the southern and western parts of the Baikal rift zone, which are therefore currently accumulating elastic strain to be released in future earthquakes. Considering the date of the last major event (1742 event, $M=7^{3/4}$, which released about 50% of the seismic moment of the South Baikal region in the past 300 years) and a constant far-field extension rate of 4.5 mm/yr, we can infer that the South Baikal fault has accumulated 2.7 m of potential slip (average displacement) since that time. This would correspond to a M=7.5 earthquake if it were to be released in a single event (Wells and Coppersmith, 1994). If magnitude 7.5-7.7 earthquakes (about 3 m of potential slip accumulation) are characteristic of the South Baikal fault zone (an assumption that is compatible with our historical knowledge and with its 150 km long continuous rectilinear trace as underlined by the instrumental seismicity), a constant far-field extension rate of 4.5 mm/yr would imply a 350-yr recurrence interval for such events. In the central lake, the numerous sub-parallel faults make such prediction more questionable, but may indicate a smaller recurrence interval (150 years) for a M=7.5 event.

Table 2. List of large historical earthquakes and main border faults in the South Baikal rift. Estimated magnitudes (M) are taken from Solonenko (1977). Seismic moments (Mo) are expressed in 10^{20} Nm. SB= South Baikal, CB=Central Baikal. See Figure 1 for fault and event locations.

Area	Event date	M	Mo	Associated fault	Length	Dip
SB	06/27, 1742	$7^{3/4}$	3.7	Obruchevsky	150 km	60°
SB	10/24, 1769	$7^{1/4}$	0.9	Obruchevsky	150 km	60°
SB	04/11, 1902	6.9	0.2	Obruchevsky	150 km	60°
CB	01/12, 1862	$7^{1/2}$	1.8	Morskoy	200 km	50°
CB	11/26, 1903	6.8	0.2	Morskoy	200 km	50°
CB	08/29, 1959	6.8	0.2	Morskoy	200 km	50°

Comparison with deformation models of Asia

Several kinematic models have been proposed recently to explain the present-day deformation in central Asia, based on Quaternary fault rates (Avouac and Tapponnier, 1993; Peltzer and Saucier, 1996) and sparse geodetic results (Molnar and Gipson, 1996; England and Molnar, 1997) or moment tensors of large earthquakes (Holt et al., 1995). Whether these models use a continuum or a rigid block approach, they all use the India/Eurasia convergence as a kinematic boundary condition to the south. They predict an extension rate that varies between 0-1 mm/yr (Peltzer and Saucier, 1996) and a maximum of 2 mm/yr (England and Molnar, 1997) in the Baikal rift zone, which is significantly smaller than our GPS results. An alternate modeling approach has recently been proposed by Kong and Bird (1996) who used a dynamic thin-shell finite-element model taking into account both the India-Eurasia and Pacific-Eurasia convergence as boundary conditions. Their best fit model predicts 19 mm/yr of extension in the Baikal rift zone, which is four times higher than our GPS results. The high heat flow values (and consequently low lithospheric thickness) used by these authors for the Baikal rift (110 to 130 mW/m^2) compared to the average value of 70 to 90 mW/m^2 given by Lysak (1992) could partly explain such a discrepancy.

The fact that the GPS-derived extension rate in the Baikal rift zone is faster than the predictions of kinematic models based on the hypothesis that present-day deformation in central Asia is enterely driven by the India/Eurasia collision suggests the existence of an additional process participating in the present-day opening of the Baikal rift zone. It has long been suggested that the Baikal rift zone was the result of "active rifting", with crustal extension primarily caused by the diapiric upwelling of a mantle asthenolith or plume (e.g. Zorin, 1981). However, recent results from gravity models (van der Beck, 1997; Petit et al., 1997), finite-element deformation models (Lesne et al., 1998), P-wave delay-time tomography (Petit et al., in press), and geochemistry of mantle xenoliths (Ionov et al., 1995) show very little mantle uplift under the Baikal rift zone and suggest that the present-day extension is mostly driven by horizontal forces related to the far-field kinematics. If local processes do not significantly contribute to the force balance in the Baikal rift zone, the additional dynamic contribution suggested by our GPS results must be sought in boundary forces not accounted for in classical deformation models, in particular at the Pacific subduction zone, whose dynamic effects on lithospheric stresses and strain in continental Asia are poorly known. Possible processes that could significantly influence the force balance several thousands of kilometers inland from the Pacific subduction include the effect of shear traction in the subduction zone (Kong and Bird, 1996) and the influence of the sinking oceanic lithosphere on the neighboring subcontinental convection by a lateral cooling effect (Nataf et al., 1981).

Conclusions

Three years of GPS measurements show that the Baikal rift zone is currently opening at a rate of 4.5±1.2 mm/yr in a NW-SE direction. Since the entire network has only be measured three times (only IRKU and ULAN have been measured four times), these results are still preliminary. They are however in good agreement with recent geological estimates of fault slip rates and with the strain and stress pattern deduced from instrumental seismicity.

VLBI results at Shanghai (Heki, 1995; Molnar and Gipson, 1996) show 8±0.5 mm/yr of eastward motion of South China relative to Eurasia. Zhang et al. (1998) determine a Plio-Quaternary extension rate of 5±2 mm/yr in a NW-SE direction across the Ordos graben system, that probably accounts for part of the South China-Eurasia relative motion. Our GPS results show 4.5±1.2 mm/yr of NW-SE extension across the Baikal rift zone, a value that is consistent with the results mentioned above. The strain in the Baikal region is however localized on a narrow (50 to 100 km wide) rift structure which appears to be concentrating the present-day deformation between Eurasia and East China.

A comparison between the GPS results and the seismic moment released by historical earthquakes suggests that elastic strain is currently accumulating in the Baikal rift zone along active faults that have the potential for a M=7.5 earthquake if that elastic strain were to be released in a single event today. If aseismic slip is neglected, we hypothesize recurrence intervals of 150-350 years for large (M~7.5-7.7) events along the lake shoreline, which could imply the occurrence of a strong shock in the near future.

The rather high extension rate found here for the Baikal rift zone compared to the prediction of most deformation models of Asia could reflect the dynamic effect of the Pacific-Eurasia subduction in addition to the well-kown effect of the the India-Eurasia collision. This hypothesis needs to be confirmed by additional GPS measurements and further tested using dynamic deformation models.

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