Imprint of the North American plate in Siberia revealed by GPS

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Received 22 May 2003; revised 28 July 2003; accepted 1 August 2003; published 17 September 2003.

[1] GPS observations in east Siberia combined with global observations, collected 1995–2002, place constraints on the geometry and motions of the Eurasian, North American, and Pacific plates in east Asia. By comparing velocities relative to Eurasia and to North America, we conclude that east Siberia to the east of the Cherskiy Range belongs to the North American plate, hypothesized for three decades but not proven because of uncertainties with the plate boundary arising from the ambiguous seismicity. Smaller plates in east Asia, such as Okhotsk and Amurian, can neither be resolved nor excluded by the GPS velocities. *INDEX TERMS:* 1229 Geodesy and Gravity: Reference systems; 1243 Geodesy and Gravity: Space geodetic surveys; 8150 Tectonophysics: Plate boundary—general (3040); 8158 Tectonophysics: Plate motions—present and recent (3040). **Citation:** Steblov, G. M., M. G. Kogan, R. W. King, C. H. Scholz, R. Bürgmann, and D. I. Frolov, Imprint of the North American plate in Siberia revealed by GPS, *Geophys. Res. Lett.*, *30*(18), 1924, doi:10.1029/2003GL017805, 2003.

1. Introduction

[2] The geometry of the Eurasia - North America plate boundary in east Asia has been discussed since the 1970s, with varying interpretations of diffuse seismic belts in east Siberia and adjacent marginal seas (Figure 1). Some authors [*Chapman and Solomon*, 1976; *DeMets*, 1992] prefer a scenario of only three plates: Eurasian (EUR), North American (NAM), and Pacific (PAC); others propose additional microplates such as Okhotsk [*Seno et al.*, 1996] and Amurian [*Zonenshain and Savostin*, 1981]. The commonly used global plate model NUVEL-1A adopts the three-plate scenario for east Asia, with the triple junction near northern Japan [*DeMets et al.*, 1994]. The goal of this study was to determine the motion and boundaries of the major plates in the region and evaluate evidence for independently moving microplates from analysis of continuous and survey mode GPS observations in east Siberia including Chukotka and Kamchatka.

[3] The geodetic solution presented here differs from our earlier solution [*Kogan et al.*, 2000] in three aspects: (1) enhanced geometrical strength because of new GPS observations in Siberia; (2) more robust realization of the North American and Eurasian plates; (3) less sensitivity to errors that cause a translation of the reference frame.

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0094-8276/03/2003GL017805$05.00

2. GPS Data and Analysis

[4] Three sources of GPS data are important to this study: continuous and survey-mode measurements in eastern Russia begun under Project RUSEG in 1995, continuous observations of the global network operated under the auspices of the International GPS Service (IGS) since 1994, and continuous observations in the western Pacific under Project WING [*Kato et al.*, 1998]. We incorporated into our analysis the data collected between July 1995 and September 2002.

[5] We used the GAMIT software [*King and Bock*, 2002] to process the GPS phase observations at stations of the regional network together with 6–7 nearest stations of the IGS global network, estimating for each day station coordinates and parameters representing the satellites' orbits, Earth orientation, and atmospheric delay. We then used the GLOBK Kalman filter [*Herring*, 2002] to combine station coordinates and their covariances, considered as quasi-observations [*Dong et al.*, 1998], with similar solutions for the IGS network available from the Scripps Orbital and Permanent Array Center (SOPAC). To reduce the short-term scatter and better evaluate the temporally correlated errors, we aggregated the daily solutions for 5–30 days to produce 208 epochs of quasi-observations at 76 stations (Table 2C[1]). Finally, combination of these quasi-observations yielded a single solution for positions and velocities over the full span of the data. At each step of the processing, we imposed on the station coordinates only loose constraints so that the definition of the reference frame could be made consistently at the end.

[6] We adopted an error model for the observations that reflects both the scatter in the (~monthly) estimates of position and the likelihood of significant temporal correlations. The solution presented here was generated by adding 2 mm of random and 2 mm/(yr)$^{1/2}$ random walk noise to the uncertainty of horizontal position of all stations from each ~monthly solution.

3. Reference Frame and Comparison With Other GPS Solutions

[7] The loosely constrained, multi-year solution implicitly provides a free-network polyhedron, in which the inter-station velocities are well determined but the overall rotation is not yet defined. The reference frame onto which we map

[1] Auxiliary material (Tables 1–4) is available at ftp://ftp.agu.org/apend/gl/2003GL017805.

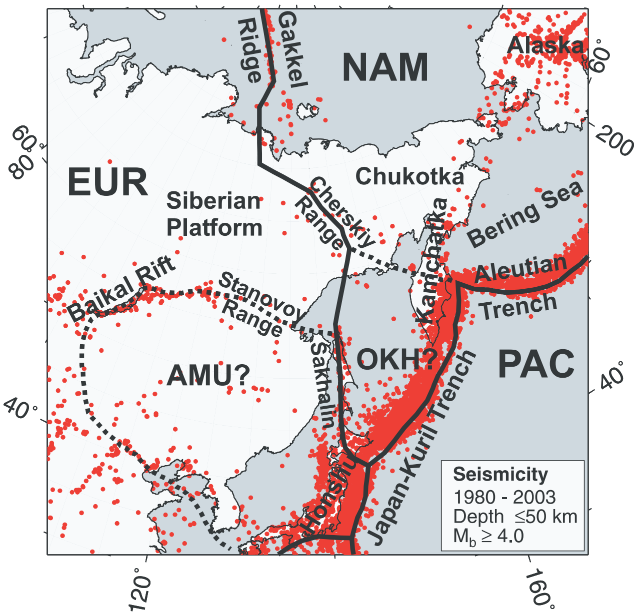

Figure 1. Tectonic sketch of northeast Asia. Eurasian (EUR), North American (NAM), and Pacific (PAC) plate boundaries according to *Chapman and Solomon* [1976]. Hypothetical Amurian (AMU) and Okhotsk (OKH) microplates according to *Seno et al.* [1996] and *Wei and Seno* [1998]. Earthquake locations (red dots) are from the USGS NEIC catalog.

the inter-station velocities is arbitrary and can be chosen to best study a particular tectonic problem. For example, to investigate deformation within and around a single tectonic plate, we can minimize the motions of all stations within the stable interior of the plate (e.g., *Chen et al.* [2000]; *Kogan et al.* [2000]). Since the uncertainty in velocity with respect to the frame-defining network will grow with distance from the network, due to the uncertainty in the angular velocity, a single-plate frame becomes less attractive for studying deformation in a boundary zone that is wide and distant from the stable area of either adjoining plate. A more robust approach is to define the frame using stations within the stable interiors of the adjoining plates, minimizing the velocities within each plate while estimating the rotation vectors (RV) between the plates. For this study we defined a three-plate frame using 18, 14, and 6 stations on the EUR, NAM, and PAC plates, respectively (Figure 2). The weighted rms horizontal velocity within each plate is ~1 mm/yr, comparable to the rms obtained for NAM by *Gan and Prescott* [2001] and *Sella et al.* [2002], and for PAC by *Beavan et al.* [2002]. This value can be considered an upper bound on both the errors and deformation within the plate interiors. Estimated RVs and velocities from our solution are given in Tables 1 and 2.

[8] Our methodology for estimating RVs differs in one potentially important respect from our earlier work [*Kogan et al.*, 2000] and that of other investigators (e.g., *Sella et al.* [2002]; *Altamimi et al.* [2002]). Rather than constraining the translation of the solution by minimizing the velocities of a set of global stations with respect to the International Terrestrial Reference Frame (ITRF2000) [*Altamimi et al.*, 2002], we allowed the solution to translate from epoch to epoch and estimated translation rate parameters simultaneously with the RVs (see a discussion in Appendix C of *Dong et al.* [1998]). This approach makes the estimated relative RVs insensitive to errors in the translation rate of ITRF2000 or in the velocities of the stations used to effect the alignment. Since the translation rate of ITRF2000 has been determined by satellite laser ranging observations and shown to be small (<0.5 mm/yr) [*Altamimi et al.*, 2002], we would not expect constraining it to have a large effect on our RV estimates, and in fact this is true. If we apply the ITRF2000 constraint, our estimates change at the level of the uncertainties. For comparison we have included these estimates in Table 1A.

[9] If we constrain the relative RVs for the three plates to their NUVEL-1A values, the weighted rms is a factor of two larger than for our GPS-consistent values. This result is not surprising since the EUR-PAC and NAM-PAC rotation rates estimated from GPS are higher than the NUVEL-1A values by 7% and 4%, respectively (Table 1A). Significant differences between geodetic and geologic plate models were also reported by previous studies (e.g., *Sella et al.* [2002]).

[10] In Table 1 we compare our estimates of the relative rotation poles for the three plates with NUVEL-1A and two recent geodetic estimates. The largest difference is for the EUR-NAM rotation vector estimated by *Altamimi et al.* [2002] from the GPS, VLBI, and SLR velocities used for ITRF2000. The primary reason for this difference does not lie in the velocities themselves, but rather in the non-uniform sampling of the Eurasian plate in ITRF2000, with most stations concentrated in Europe. If we use our solution but with the stations used by *Altamimi et al.* [2002], the estimate matches theirs closely (Table 1B). For PAC-NAM, our pole is consistent with the GPS solution of *Beavan et al.* [2002].

4. Plate Kinematics of Northeast Asia

[11] To assess possible plate configurations in northeast Asia, we compare our GPS velocities relative to Eurasia and

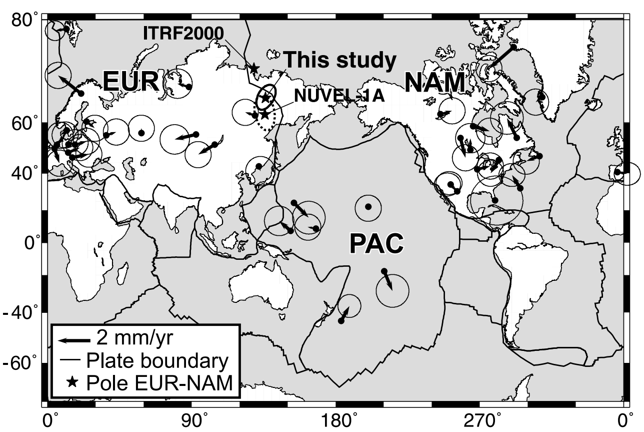

Figure 2. Residual velocities of 38 stations within the stable plate interiors with respect to the EUR, NAM, and PAC plates. Rotation poles for EUR-NAM estimated in this study, NUVEL-1A [*DeMets et al.*, 1994], and ITRF2000 [*Altamimi et al.*, 2002] are shown with stars. Ellipses for velocities are one standard error (39% confidence in two dimensions), and for the rotation poles are 2.45 standard error (95% confidence).

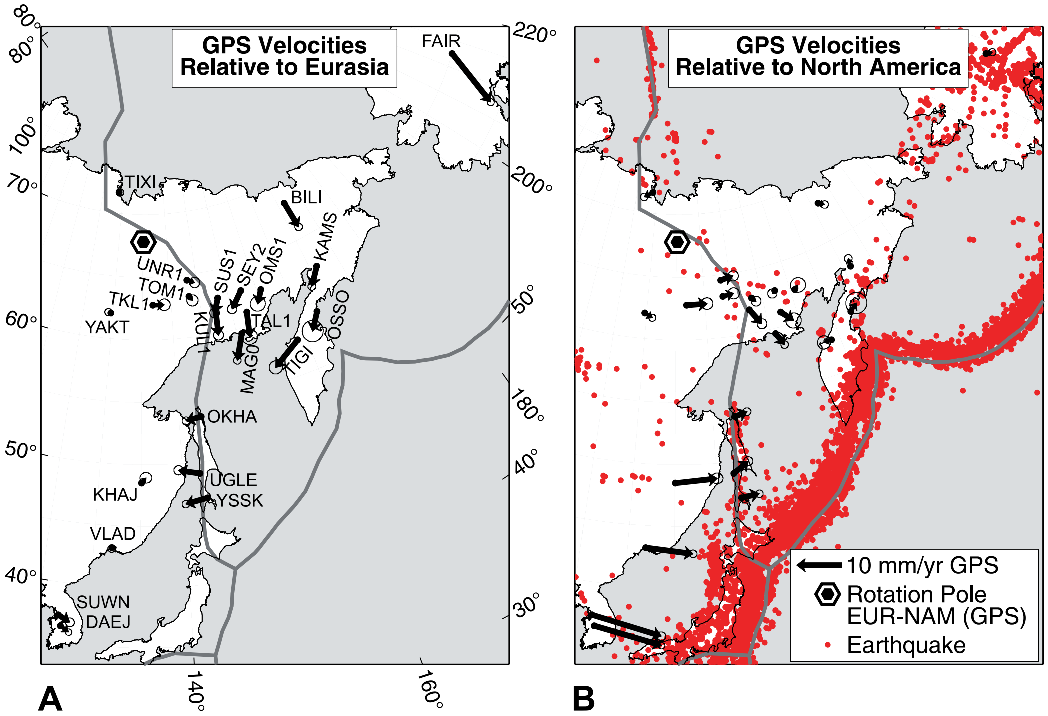

Figure 3. (A) GPS velocities in northeast Asia relative to the Eurasian plate for stations far from subduction zones. Ellipses for velocities are one standard error. The hexagon indicates the location of our estimated pole for EUR-NAM. The OKH-EUR pole estimated by *Seno et al.* [1996] (not shown) from earthquake slip vectors is located at northern Sakhalin (53N, 142E). (B) Same as (A), but relative to the North American plate. The OKH-NAM pole estimated by *Seno et al.* is located near SE Hokkaido (42N, 147E).

to North America. Relative to EUR (Figure 3A, Table 3A), the velocities are <2 ± 1 mm/yr for stations on the western flank of the Cherskiy Range and in the Siberian craton. The velocities are much higher, 3 to 8 mm/yr, for stations on the eastern flank of the Cherskiy Range, in Chukotka, and in northwestern Kamchatka; the sense of motion indicates the clockwise rotation of the region relative to EUR. Stations in the region of the Cherskiy Range can be affected by the distributed deformation at the convergent EUR-NAM boundary. The rate of convergence, however, is small, <1–3 mm/yr, because of the proximity of the pole, so we can assume that the effect of strain accumulation is also small and becomes negligible at a distance >100 km from the boundary.

[12] Relative to North America (Figure 3B, Table 3B), the velocities are <2 ± 1 mm/yr in Chukotka and in northwestern Kamchatka. Of the six stations on the eastern flank of the Cherskiy Range, the three northernmost stations (SUS1, SEY2, and OMS1) move slower than 1 mm/yr, while the other three (MAG0, KUL1, and TAL1) move at 2–3 mm/yr. The velocities on the western flank of the Cherskiy Range and in the Siberian craton are 2–11 mm/yr; they indicate anticlockwise rotation in agreement with the EUR-NAM rotation vector. We conclude that GPS velocities in east Siberia confirm the western branch of the Cherskiy Range seismic belt as the northeastern boundary of Eurasia. The velocity of station TIXI near the Arctic margin of Siberia is smaller relative to Eurasia than relative to North America. Therefore we suggest that the EUR-NAM divergence in this area occurs mostly to the east of TIXI.

[13] To explain the earthquake slip vectors in the Sea of Japan - Sea of Okhotsk region, *Seno et al.* [1996] proposed clockwise rotation of an Okhotsk microplate (OKH) with respect to Eurasia about a pole near northern Sakhalin. In our solution three stations near Magadan (MAG0, TAL1, KUL1) move southeast relative to North America (Figure 3B). Station TIGI in western Kamchatka shows insignificant motion with respect to NAM. However, if we remove the motion of TIGI predicted by the elastic strain accumulation from subduction of the Pacific plate, the station's velocity relative to NAM is southeast at 2 ± 3 mm/yr, roughly consistent with the stations near MAG0. The direction of motion of these four stations is more southerly than predicted by the OKH-NAM rotation vector estimated by *Seno et al.* [1996] from the earthquake slip vectors. More appealing is southward extrusion of the Okhotsk plate caused by convergence between Eurasia and North America [*Riegel et al.*, 1993]. The only other stations on land within the proposed region of the Okhotsk plate are on Sakhalin Island (OKHA, UGLE, YSSK), in a complex deformation zone between EUR and NAM or OKH (see, e.g., *Kogan et al.* [2003] and references therein). Associating any part of Sakhalin with a rigid plate will be difficult and will require a much greater density of measurements than are currently available. Hence, geodetic evidence for an Okhotsk plate is limited to the velocities of stations near Magadan and western Kamchatka, which represent only a small fraction of the proposed plate and can be equally well interpreted as motion of a block of much smaller dimensions.

[14] An Amurian plate (AMU) was first proposed to explain the pattern of regional seismicity, relatively strong around Lake Baikal but diffuse across the Stanovoy Range and northern China [*Zonenshain and Savostin*, 1981; *Wei and Seno*, 1998] (Figure 1). However, the rotation rate of AMU with respect to EUR estimated by *Wei and Seno* [1998] from earthquake slip vectors is so small that their predicted velocities are <1 mm/yr everywhere in AMU. Recent geodetic studies indicate that spreading across the Baikal rift is 4–5 mm/yr [*Calais et al.*, 2002], suggesting that if AMU moves as a rigid block, its motion should be detectable with GPS measurements. To estimate an RV for AMU with respect to EUR, we combined our velocities for VLAD, DAEJ, and SUWN with the velocity obtained by *Calais et al.* [2002] for ULA1 in eastern Mongolia. If we correct the velocity of ULA1 using the model of *Calais et al.* [2002] for post-seismic effects of two magnitude 8 earthquakes which struck 600 km to the west in 1905, motion of the three regions (SE Russia, Korea, and Baikal) is consistent (rms 0.9 mm/yr) with a rigid-body rotation of 0.11 ± 0.03 deg/Myr about a pole near Vladivostok (48N, 133E). *Sella et al.* [2002] obtained a similar rate but with the pole 2,000 km to the east using only VLAD, DAEJ, and SUWN. Both pole results should be viewed with caution, however, since there is little redundancy in the estimation. Localized or distributed deformation east of the Baikal rift zone and around Korea represent an equally valid hypothesis to explain the motions of stations in these regions. Our velocities for VLAD, DAEJ, and SUWN are not consistent with the much more rapid motion of AMU inferred by *Heki et al.* [1999]. Their velocities were first estimated with respect to ITRF and then converted to the Eurasian reference frame using the VLBI velocity of a single station Tsukuba (TSKB). This velocity differs from other recent geodetic solutions, including ours, by ~6 mm/yr in the east component [*Chen et al.*, 2000; *Wang et al.*, 2001; *Altamimi et al.*, 2002; *Sella et al.*, 2002] (Table 4).

5. Conclusions

[15] As evidenced by velocities derived from GPS observations collected over a 4- to 6-year period, Siberia to the east of the Cherskiy Range, including Chukotka and Kamchatka, belongs to the North American plate. The velocities of some stations within the proposed Okhotsk and Amurian microplates are as much as 3–5 mm/yr relative to North America and Eurasia, respectively, but the small number and limited geographical distribution of these stations precludes clear association of their velocities with rotation of rigid plates rather than distributed deformation.

[16] **Acknowledgments.** This study was supported with NSF grants EAR 0106999, 0106002, and 0105587 to LDEO, UC Berkeley, and MIT, respectively; and by JPL grant 1203235 and IRIS grant 311 to LDEO. We thank Sergey Egorov for contributing to GPS surveys over the Cherskiy Range in 1996–2002, and Tom Herring for discussions and enhancements to the GLOBK software that made this study possible. Figures were drawn with the GMT software [*Wessel and Smith*, 1998].

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