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Independent active microplate tectonics of northeast Asia from GPS velocities and block modeling

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[1] Independent Okhotsk and Amurian microplate motions are tested using velocities from 123 GPS sites (80 from within the proposed OKH and AMU plate boundaries) used to constrain the plate kinematics of northeast Asia. A block modeling approach is used to incorporate both rigid block rotation and near-boundary elastic strain accumulation effects in a formal inversion of the GPS velocities. Models include scenarios with and without independent OKH and AMU plate motion. Our modeling favors scenarios with independent OKH and AMU motion, based on the application of F-test statistics. The independent OKH plate rotates 0.231 deg/Myr clockwise with respect to North America about a pole located north of Sakhalin. The modeled AMU plate rotates 0.298 deg/Myr counterclockwise with respect to NAM about a pole located west of the Magadan region. The plate-motion parameters of the independent plates are consistent with the kinematics inferred from earthquake focal mechanism solutions along their boundaries. **Citation:** Apel, E. V., R. Bürgmann, G. Steblov, N. Vasilenko, R. King, and A. Prytkov (2006), Independent active microplate tectonics of northeast Asia from GPS velocities and block modeling, *Geophys. Res. Lett.*, *33*, L11303, doi:10.1029/2006GL026077.

1. Introduction

[2] Northeast Asia is one of the last plate tectonic frontiers in the world. Boundaries between the North American (NAM) and Eurasian (EUR) plates are uncertain, and remain enigmatic due to the possible independent rotation of smaller microplates (such as the proposed Okhotsk, Amurian, and Bering microplates) within the broader plate-boundary zone. Elucidating the current plate kinematics of the region is further complicated by subduction-dominated deformation in the east and little differential plate motion in the west resulting in diffuse and sparse seismicity obfuscating the plate boundaries.

[3] The possible existence of independently rotating Okhotsk (OKH) and Amurian (AMU) microplates has been examined by many in an attempt to explain both seismological and geologic data in Northeast Asia [*Cook et al.*, 1986; *Riegel et al.*, 1993; *Seno et al.*, 1996]. Geodetic measurements can be used to fully characterize the motion of tectonic plates; however, because most GPS sites in this region are in such close proximity to plate boundaries, previous attempts to confirm or refute an independent OKH plate have been inconclusive [*Heki et al.*, 1999; *Takahashi et al.*, 1999; *Steblov et al.*, 2003]. Establishment of independent AMU plate motion has remained as elusive because of the uncertainty of the southwestern plate boundary and fewer plate-interior GPS sites [*Petit and Fournier*, 2005].

[4] Horizontal surface velocities of 123 GPS sites (80 from within the proposed OKH and AMU plate boundaries) allow for a rigorous test of the possibility of independent OKH and AMU plate motion. We use a block modeling approach to incorporate both rigid block rotation and near-boundary elastic strain accumulation effects in a formal inversion of the GPS velocities. We consider models that include scenarios with and without independent microplates.

2. Plate Boundaries

[5] The first challenge in establishing a plate tectonic model of northeast Asia lies in defining the boundaries of the major and minor plates in the region. While some boundaries are well defined by active fault traces, youthful geomorphology, and abundant localized seismicity, others appear diffuse and ambiguous. We draw on the distribution and kinematics of 20th century seismicity, local geology and mapped faults, and the GPS velocity field itself to define our model block boundaries.

[6] Figure 1 shows the seismicity of northeast Asia, dominated by subduction of the Pacific plate along Kamchatka and southward along the Kurile Islands and Japan. Seismicity in the north (Chersky range) and the west (Magadan region) is sparse and diffuse. Sakhalin Island exhibits large magnitude events that reflect both contractional and right-lateral faulting [*Kogan et al.*, 2003]. North of Sakhalin in the northeast Okhotsk Sea, seismicity is notably absent. West of Sakhalin, earthquakes become more frequent but substantially more diffuse along the Stanovoy Mountains. Active rifting is distinct through the Baikal region, although the distribution of earthquakes becomes substantially more diffuse through central Mongolia and northern China. Seismicity, while useful for examining plate boundary geometry and general deformation styles, does not provide a complete picture of the plate kinematics of the region. In areas of diffuse seismicity we augmented earthquake data with active fault maps [*Greninger et al.*, 1999], and other published boundary models [*Bird*, 2003; *Petit and Fournier*, 2005].

[7] Finally, we use the constraints provided by the GPS velocity field itself to test variable geometries where the

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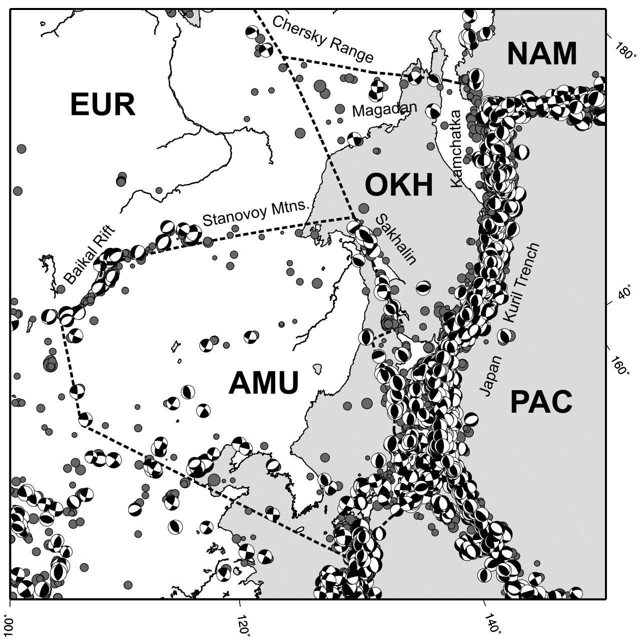

Figure 1. Seismicity of northeast Asia. Hypocenters (solid circles) are sized by magnitude and plotted to a depth of 35 km from the *Engdahl et al.* [1998] catalog. Focal mechanisms are from Harvard CMT catalog (http://www.seismology.harvard.edu/CMTsearch.html). Plate boundaries (dashed lines) are from this study.

seismicity does not paint a clear picture of the plate boundary geometry. This allows us to refine the model geometry along the Kamchatka and Japan subduction zones and to test different plate boundary scenarios along the Sakhalin deformation zone. However, the lack of dense GPS coverage in Siberia and over the northeastern OKH crust precluded the boundaries in these regions from further improvement and from being significant in the block modeling.

3. GPS Velocities

[8] The GPS velocities used in our inversion are from an updated velocity field of 151 global stations by *Steblov et al.* [2003]. We include observations from additional campaign stations from central Sakhalin [*Kogan et al.*, 2003] and the Kamchatka peninsula [*Bürgmann et al.*, 2005], and from 18 stations in northern Japan that are part of the continuous network (GEONET) operated by the Geographical Survey Institute. Details of the data analysis using GAMIT/GLOBK are given by *Steblov et al.* [2003].

[9] In addition to our own analysis we included from published work GPS velocities that help to define the deformation patterns for the Baikal and central AMU regions [*Calais et al.*, 2003] and selected stations from *Zhang et al.* [2004] that fell within or near the boundaries of the proposed AMU microplate. We integrated these velocities into the reference frame of our own solutions by estimating translation and/or rotation parameters that minimized the differences in horizontal velocities for common sites. 123 sites were selected from the combined solution for our inversion including locations within the 'stable' plate interiors of the Pacific, North American, and Eurasian plates (see auxiliary material[1]). Velocities in our area of interest are shown in Figure 2.

4. Block Modeling

[10] Testing for independent plate rotation is accomplished by determining a best-fit pole of rotation on a spherical earth that matches surface velocities for sites that lie within a 'stable' plate interior [e.g., *Larson et al.*, 1997; *Sella et al.*, 2002]. However, regions like northeast Asia require a more sophisticated approach because many (if not all) of the measured velocities contain components of both rigid block motion and plate boundary strain. By modeling plate boundary deformation at block edges we can separate the velocity contribution from elastic strain accumulation from the rigid block motion and test for independent plate motion [e.g., *Matsu'ura et al.*, 1986; *McCaffrey et al.*, 2000].

[11] Our approach combines aspects from the above mentioned studies by defining our plates as rigid blocks in a spherical framework bounded by dislocations in an elastic halfspace [*Okada*, 1985]. We invert for poles and rates of rotation for each block using the block modeling code by *Meade and Hager* [2005] that implements our approach by minimizing the misfit to the GPS velocities. The segments that bound the blocks represent uniformly slipping elastic dislocations locked to some specified depth. Because our inversion combines rigid block rotation with elastic strain accumulation effects, the parameterization of the block boundary geometry is critical for GPS measurements located within several locking depths of the block boundary. Geometry of the block boundaries is based heavily on seismicity (as discussed in section 2), adopted from prior analyses [*Mazzotti et al.*, 2000; *Bürgmann et al.*, 2005; *Toya and Kasahara*, 2005] or adjusted as indicated by the geodetic data [*Kogan et al.*, 2003].

[12] Subduction zones are represented by discrete dipping dislocations locked to ~40 km depth (see auxiliary material for complete individual block segment parameters) and allowed to accommodate both strike-slip and dip-slip motion. Diffuse boundaries surrounding the OKH region in the northern and western edges are not manifested as discrete fault zones. With the exception of the Baikal region, the AMU region is also bounded by zones of distributed and complex faulting. These plate boundary deformation zones are represented in our model by vertical dislocations locked to depths of 70 km that are allowed both strike-slip and opening motions. Seventy percent of the displacement gradient across such boundaries is distributed across a distance equivalent to two locking depths.

[13] We invert the horizontal GPS velocities for poles of rotation constrained by the prescribed block geometry. Systematic patterns in the residual velocities (observed minus predicted) are used as an indicator of where and how the model matches the observed surface velocities.

[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2006gl026077.

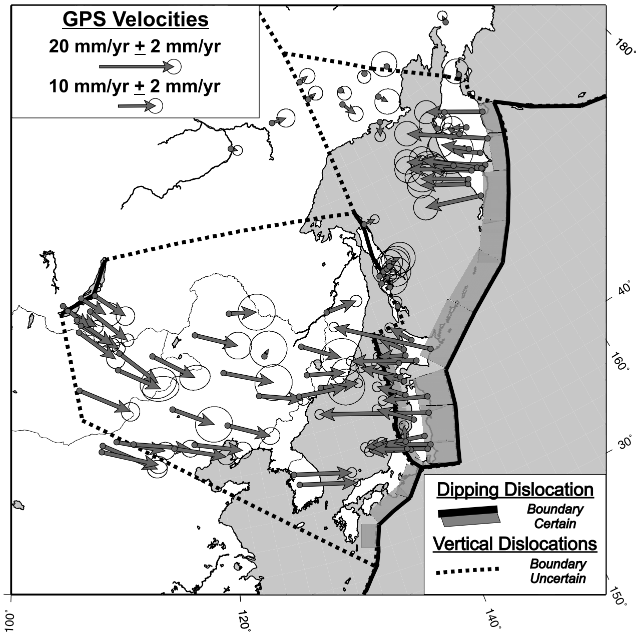

Figure 2. Combined GPS velocities from continuous, campaign, and published data. 90 of the 123 velocities are shown here in a fixed North American reference frame. The remaining far field sites are outside the range of the figure and can be seen in the auxiliary material. Plate boundaries shown in this figure reflect their geometry and certainty.

Misfit statistics are used to formally evaluate the statistical significance of the plate kinematic scenarios we test.

5. Results

[14] Independent OKH plate motion is tested using three main block configurations. In our 3-plate model we include the NAM, EUR, and Pacific (PAC) blocks. We assume that the Okhotsk region is part of the NAM plate and Amuria belongs to Eurasia [*Steblov et al.*, 2003]. Our 4-plate model allows the OKH block to rotate independently while the 5-plate model includes an additional independently rotating AMU block. We then compare the misfit of each inversion to test for significance using F-statistics [*Stein and Gordon*, 1984]. The chi-squared statistics are summarized in Table 1.

[15] Our 3-plate model shows a clear, systematic pattern of residual velocities that suggests independent OKH plate motion (Figure 3). In our 4-plate model the improvement in fit measured by the chi-squared misfit for the OKH sites is reduced from 786.2 to 476.7 (Table 1). The calculated F-statistic between the 3-plate and the 4-plate model is 51.97, well above the 99% confidence level of 3.87. Rotation vectors calculated from our optimized 4-plate inversion, suggest the OKH block rotates 0.231 ± 0.013 deg/Myr clockwise, with respect to NAM, about a pole located north of Sakhalin (Figure 4).

[16] The addition of an independently rotating AMU block in our 5-plate inversion reduces the misfit by rotating counterclockwise about a pole of rotation west of the Magadan region at 0.289 ± 0.017 deg/Myr. Our 5-plate model shows a decrease in the chi-squared misfit from the 4-plate system by reducing the misfit of AMU sites from 105.1 to 53.9 (Table 1). The calculated F-statistic between the 4-plate and the 5-plate model is 30.17, above the 99% confidence level of 2.88.

[17] Our inversions favor a scenario with both independent OKH and AMU plate motion, based on the application of F-test statistics. The improvement in the fit to the data is significant well above the 99% confidence limits for both plates.

Table 1. Statistical Summary of Block Models

	3		4		5	
Blocks	n	χ^2	n	χ^2	n	χ^2
EUR	21	80.6	21	57.0	21	48.9
AMU	32[a]	115.7	32[a]	105.1	32	53.9
NAM	16	113.2	16	24.4	16	27.0
OKH	48[b]	786.2	48	476.7	48	499.7
PAC	6	14.3	6	8.5	6	8.4
Total	123	1110	123	672	123	638

[a]In the 3 and 4-block model AMU sites are assumed to be on EUR.
[b]In the 3-block model OKH sites are assumed to be on NAM.

6. Discussion and Conclusion

[18] The plate-motion parameters of independently rotating OKH and AMU plates are consistent with the style of active deformation inferred from focal mechanism solutions. For example, our inversions predict right-lateral motion in northern Sakhalin, oblique contraction in southern Sakhalin, and little to no active deformation in the submarine crust north of Sakhalin. Predicted rifting in the

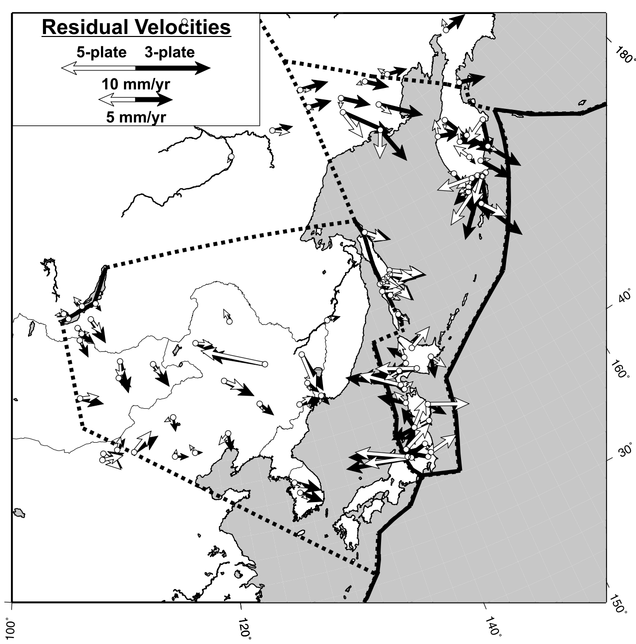

Figure 3. Residual velocities (observed minus predicted) from the 3 and 5-plate models. Residual velocities from the 3-plate model (NAM, EUR, and PAC) are shown in black; residuals from the 5-plate model are shown in white. Residuals are greatly reduced with additional independently rotating Okhotsk and Amurian plates.

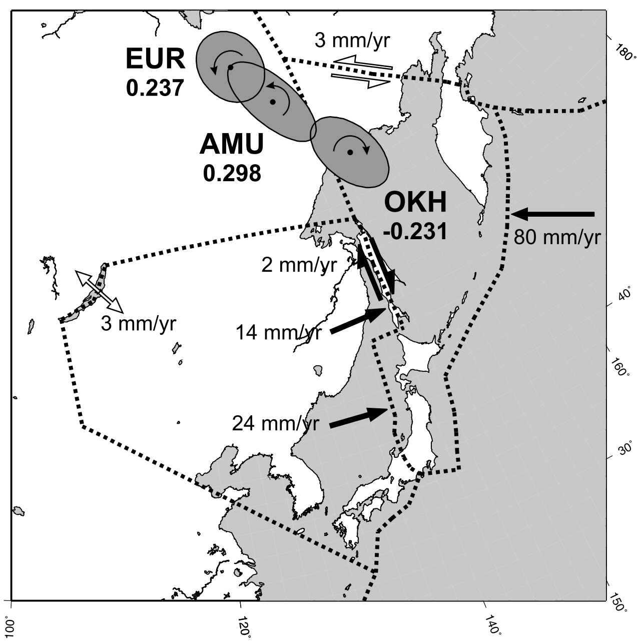

Figure 4. Calculated poles of rotation for the 5-plate model. Rotation rates are in degrees per million years with a positive counterclockwise convention. Error ellipses show 95% confidence limits. Selected slip rates from the 5-plate model are consistent with previous studies.

Baikal region is also consistent with historical seismicity and active structures.

[19] *Calais et al.* [2003] estimate opening in the Baikal rift zone at 4 ± 1 mm/yr, consistent with our estimate of 3 ± 1 mm/yr (Figure 4). Oblique contraction in southern Sakhalin is observed in the seismicity [*Kogan et al.*, 2003] and consistent with our estimates of right lateral (2 ± 1 mm/yr) oblique contraction (14 ± 2 mm/yr) in the same region (Figure 4). Further south, along the western Japanese back-arc, the convergence rates increase from to ∼15–19 mm/yr (EUR-NAM) in our 3-plate model to ∼19–28 mm/yr (AMU-OKH) in the 5-plate model (Figure 4). Calculated slip rates from our model also suggest left-lateral slip along the northern boundary (Ulakhan fault) of the OKH plate at rate of 3 ± 1 mm/yr (Figure 4). *Hindle et al.* [2006] suggest left-lateral slip rates along this fault as high as 5.5 mm/yr, similar to our estimates, although the complexities of continental deformation in this region may be under modeled.

[20] Poles of rotation for the OKH plate derived from focal mechanisms [*Cook et al.*, 1986] predict a counter-clockwise rotation with respect to North America about a pole located in northern Siberia. *Seno et al.* [1996] predict a counter-clockwise rotation of 0.195 deg/Myr with respect to North America about a pole located east of Hokkaido. More recent geodetic global plate motion models [*Sella et al.*, 2002], using 5 GPS velocities from the plate interior, predict an OKH plate rotating counter-clockwise 0.305 deg/Myr about a pole of rotation in the Sea of Okhotsk just south of the Magadan region. These poles are consistent with the ones calculated in this study (see auxiliary material for a full summary of published poles.)

[21] The systematic pattern of residual velocities in our 3-plate model is evident regardless of subtle changes made in each block model iteration (Figure 3). This pervasive systematic pattern is the most convincing evidence for an independently rotating OKH plate. In the absence of an independently rotating OKH block, residual velocities of 3–5 mm/yr show a clear rotational pattern about a point north of Sakhalin Island. Independently rotating OKH and AMU blocks are statistically significant above the 99% confidence level and consistent with the deformation types inferred from earthquake focal mechanism solutions along their boundaries.

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