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The 2000 M_w 6.8 Uglegorsk earthquake and regional plate boundary deformation of Sakhalin from geodetic data

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[1] Interseismic GPS velocities in Sakhalin indicate that the island moves to the west at 3–4 mm/yr with respect to the Eurasian plate, which is about half of the relative Eurasia - North America plate convergence rate. GPS measurements across the central Sakhalin fault system provide evidence of compressive and strike-slip strain accumulation at a rate ≤ 3 mm/yr. Coseismic vertical displacements produced by the August 4, 2000 M_w 6.8 Uglegorsk earthquake in Sakhalin were analyzed by constrained nonlinear inversion which provided evidence for a reverse faulting mechanism on an east-dipping fault plane. *INDEX TERMS:* 1206 Geodesy and Gravity: Crustal movements—interplate (8155); 8150 Tectonophysics: Evolution of the Earth: Plate boundary—general (3040); 8122 Tectonophysics: Dynamics, gravity and tectonics. **Citation:** Kogan, M. G., R. Bürgmann, N. F. Vasilenko, C. H. Scholz, R. W. King, A. I. Ivashchenko, D. I. Frolov, G. M. Steblov, Ch. U. Kim, and S. G. Egorov, The 2000 M_w 6.8 Uglegorsk earthquake and regional plate boundary deformation of Sakhalin from geodetic data, *Geophys. Res. Lett.*, *30*(3), 1102, doi:10.1029/2002GL016399, 2003.

1. Introduction

[2] Geologic plate motion models suggest that Sakhalin Island is located at the Eurasia (EUR) - North America (NAM) convergent plate boundary [*Chapman and Solomon*, 1976; *DeMets*, 1992] (Figure 1). Alternatively, a region of the Sea of Okhotsk including Sakhalin is assigned to the Okhotsk (OKH) microplate converging with Eurasia [*Seno et al.*, 1996].

[3] Central and southern Sakhalin are dominated by N–S trending reverse faults of Quaternary age while the northeastern part of the island is deformed by several right-lateral strike-slip fault zones [*Bulgakov et al.*, 2002]. Sakhalin is seismically active along its whole 900-km length, with over one hundred $M_b \geq 4.5$ events in 1977–2002 (NEIC/CNSS). Most well-determined focal mechanisms for large events in Sakhalin indicate reverse faulting with east-west trending *P*-axes [*Seno et al.*, 1996] with the exception of the M_w 7.0 1995 Neftegorsk event, which ruptured the ~N15°E striking, right-lateral strike-slip Upper Piltun fault in northeastern Sakhalin.

[4] The August 4, 2000, M_w 6.8, Uglegorsk earthquake (Figure 2) is the largest instrumentally recorded dip-slip event on the island. It occurred near the west coast of Sakhalin on a previously unrecognized fault. A north–south striking surface rupture was identified in the wooded mountainous terrain with a total observed length of only 10 km.

[5] This study addresses two questions: (1) Which fault geometry of the 2000 Uglegorsk earthquake can be inferred by inversion of the geodetic data? (2) What is the plate scenario that is most compatible with interseismic GPS velocities in Sakhalin?

2. Deformation of Sakhalin From GPS Velocities

[6] The best determined GPS stations YSSK (Yuzhno-Sakhalinsk), UGLE (Uglegorsk), and OKHA (Okha), observed since 1995 for ≥ 5 yrs, are located within the Tym-Poronaisk and northern Sakhalin fault systems or to the west of them (Figure 1). For these three stations, we processed phase data in 24-hr sessions together with a subset of 6–7 well determined IGS global stations using the GAMIT-GLOBK software. The estimates and covariances were then combined with those computed for the entire IGS global network by the Scripps Orbit and Permanent Array Center (SOPAC). In a final step of the processing, the Sakhalin station velocities were evaluated in both the Eurasian and North American reference frames, each determined by a set of stations in stable continental interiors. Our estimates of velocities of YSSK and OKHA differ significantly from those of *Heki et al.* [1999] because their solution lacks stations within stable Eurasia.

[7] GPS velocities of YSSK, UGLE, and OKHA presented in this study are remarkably uniform, 3–4 mm/yr to the west with respect to Eurasia and 3–5 mm/yr to the east with respect to North America. The magnitude of GPS velocities with respect to either plate is 50%–100% of their convergence rate (Figure 1c).

[8] The nearly identical GPS velocities at stations YSSK, UGLE, and OKHA (southern, central, and northern Sakhalin, respectively) are more consistent with the two-plate geometry shown in Figure 1a than a three-plate geometry with the OKH-EUR pole (Figure 1b) estimated by *Seno et al.* [1996]. Correcting for the elastic strain accumulation due to Pacific plate subduction along the Japan-Kuril arc reduces the velocities in the Eurasian frame by 2–6 mm/yr in the south and 1–3 mm/yr in the north, accentuating the

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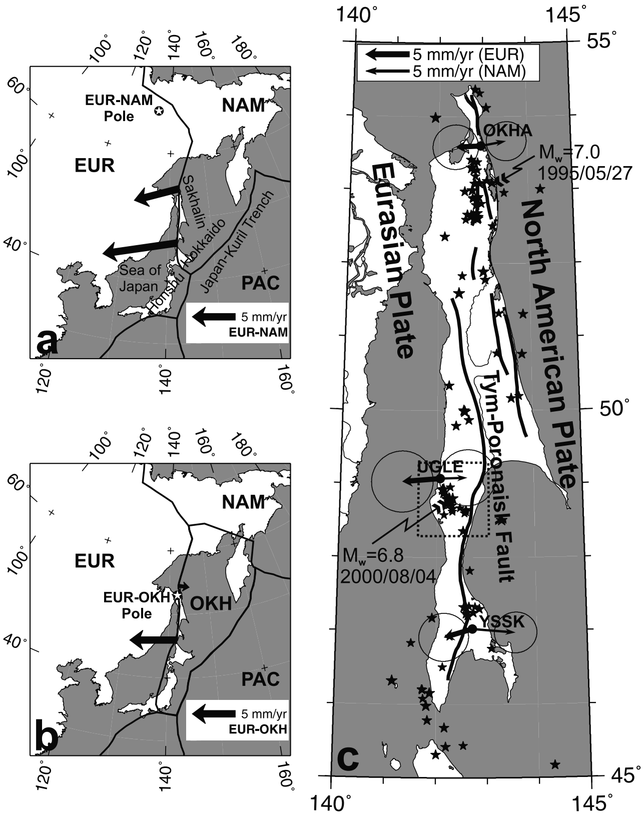

Figure 1. (a) Tectonic plate boundaries for model NUVEL1-A; the pole and rate of convergence from the updated solution of *Kogan et al.* [2000]. (b) Okhotsk microplate model of *Seno et al.* [1996]. (c) Mapped faults, seismicity, and GPS velocities in Sakhalin. Earthquakes are for the interval 1977–2002 with $M_b \geq 4.5$. Interseismic GPS velocities of stations YSSK, UGLE, and OKHA with respect to Eurasia and to North America. Ellipses correspond to 95% confidence. The dotted rectangle around the 2000 earthquake is the region shown in Figure 2.

departure from the motions predicted by the *Seno et al.* pole.

[9] In 2000 (3 months after the Uglegorsk earthquake) and in 2002, we performed GPS observations at six stations across the Tym-Poronaisk fault at 50°N and at two stations to the south (Figure 3). We assume that the observations at these sites in 2000 were unaffected by the postseismic afterslip because of their significant distance from the epicentral region and the large time since the event. The observed deformation has both compressive and strike-slip components. These data indicate that the convergence rate within the Tym-Poronaisk fault system is $\sim$3 mm/yr, about half of the EUR-NAM convergence.

3. Geodetic Observations of the 2000 Earthquake

[10] UGLE is the only station in the region of the earthquake that was observed with GPS both before and after August 4, 2000. The time series of UGLE with respect to YSSK shows that UGLE shifted to the NNW by 13 ±2mm as a result of the 2000 earthquake. Its vertical displacement could not be resolved at the level of the uncertainty (8 mm). Twenty other stations (Figure 4), are spirit leveling benchmarks measured in 1975–1986 and re-observed with GPS in October 2000 and in October 2001. Their GPS vertical uncertainties (1- σ) relative to UGLE are 5–7 mm.

[11] The spirit leveling at benchmarks was performed with an rms error of 0.5 $\text{mm/(km)}^{1/2}$ estimated from double-run observations and from circuit misclosure. To be compared with GPS (ellipsoidal) heights, orthometric elevations measured by leveling must be corrected for differences between the geoid and the ellipsoid. To calculate these corrections, we combined detailed land gravity surveys of Sakhalin and of adjacent regions of continental Asia and of Japan with the satellite altimetry gravity anomalies [*Sandwell and Smith*, 1997] over oceanic regions (Figure 4).

[12] The observed vertical displacements (Figure 4) delineate a high peaking to 1.5 m directly over the cluster of aftershocks. This deformation contains not only the coseismic signal but also motions in the preceding 25-yr period and 2 months of postseismic deformation of unknown magnitude. The repeated leveling data in Sakhalin spanning the period 1953–1977 [*Sergeev et al.*, 1981]

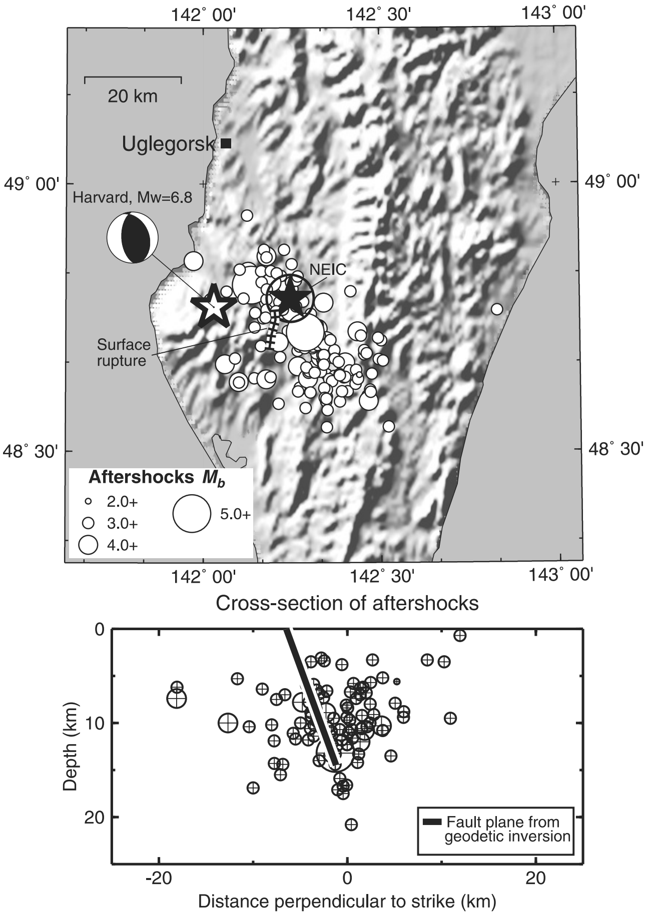

Figure 2. (Top) The main shock of August 4, 2000, and aftershocks of 5–31 August, from the temporary local seismic network of IMGG. The shaded relief is the GTOPO30 DEM of the USGS EROS Data Center. (Bottom) Depths of aftershocks within the 30-km wide band perpendicular to the strike of the line of aftershocks. The best fitting fault plane from the geodetic inversion is superimposed.

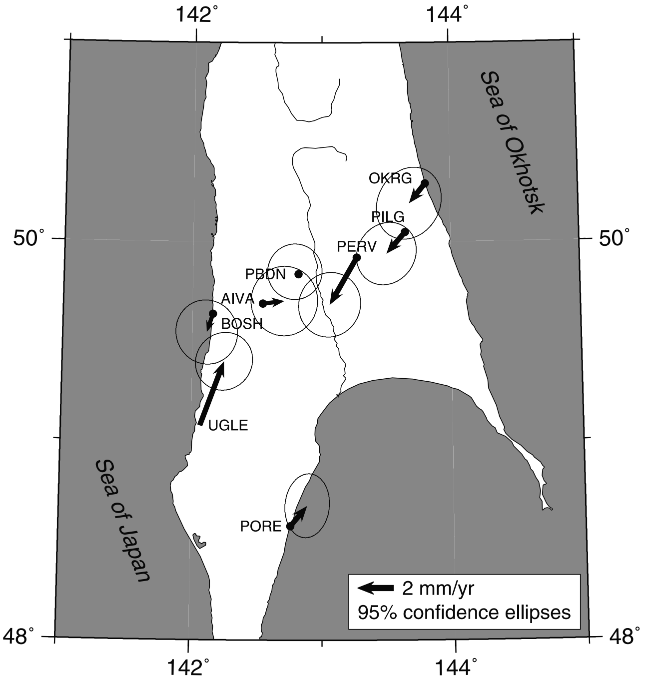

Figure 3. GPS velocities in a local reference frame for central Sakhalin from field observations in 2000, 2001 (UGLE only), and 2002. The N–S trending lines in the middle of the island are rivers. The Tym-Poronaisk Fault is located along the river valley at about 143°E.

indicate that the region of the 2000 Uglegorsk earthquake experienced uplift at a rate of 1–4 mm/yr. Hence the amount of vertical deformation in the 25-year preseismic period is less than 0.1 m assuming a constant uplift rate. The postseismic vertical motion is also unlikely to exceed 0.1 m, based on existing geodetic studies of early postseismic deformation following large continental earthquakes [e.g., *Bürgmann et al.*] and the lack of postseismic deformation between the 2000 and 2001 GPS occupations.

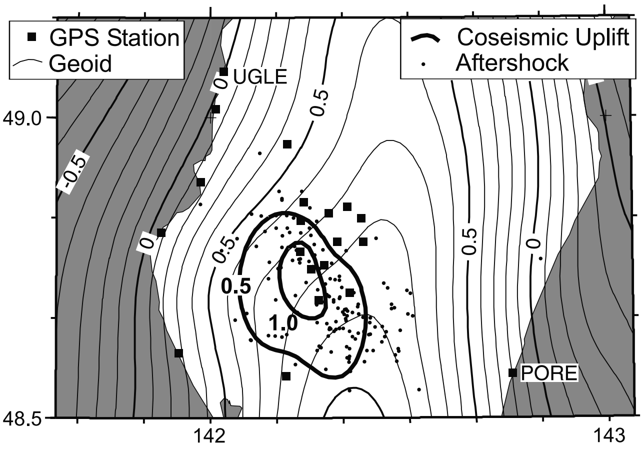

Figure 4. EGM96 spherical harmonic model of the geoid complete to degree and order 360. Corrections to EGM96 computed from the gravimetry by Stokes integration are less than 0.1 m over the epicentral region. Geoid elevations relative to the global ellipsoid are referenced to station UGLE. Vertical displacements from comparison of GPS and leveling measurements corrected for the geoid. Geoid and displacements are in meters.

4. Inversion of Earthquake Displacements

[13] We interpret the vertical displacements at 20 benchmarks and the horizontal displacement of UGLE in terms of a simple model of deformation assuming a single rectangular fault plane with uniform slip in an elastic half-space (Figure 5). The fault plane is parameterized by dimension (along-strike length and along-dip width), orientation (dip and strike), location (coordinates of the middle of the upper edge and its depth), and the amount of slip (dip and strike components). We perform an inversion using a constrained nonlinear optimization algorithm [*Bürgmann et al.*, 1997].

[14] We search for the best-fitting dislocation planes with both east- and west-dipping geometry. The model fault planes are constrained to strike and dip within ±15° of either Harvard CMT nodal plane (Table 1). Because a surface rupture has been observed, we further restrict the model space to the models reaching the surface. In the inversion for the best-fit east-dipping plane, the solution favors a steeper dip than that indicated by the seismic data,

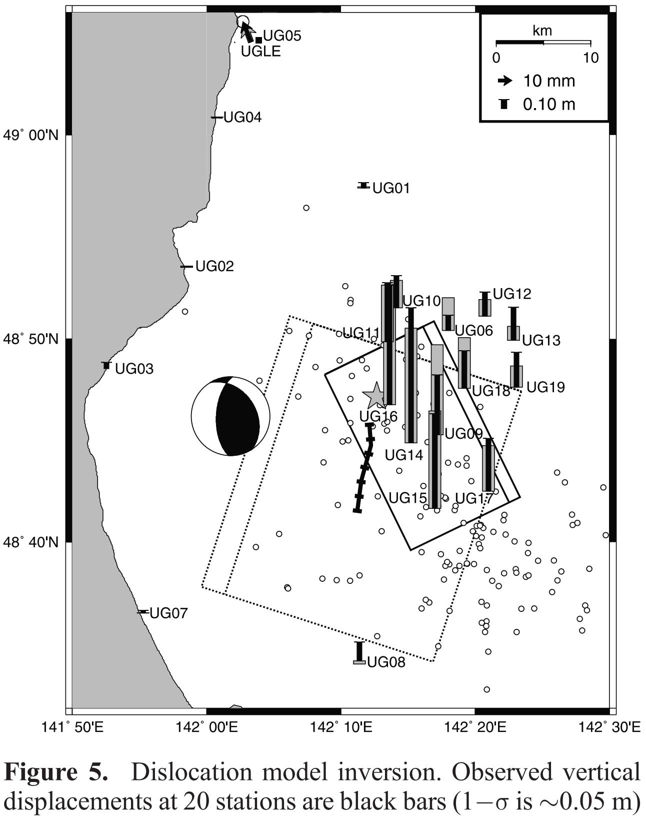

Figure 5. Dislocation model inversion. Observed vertical displacements at 20 stations are black bars (1–σ is ~0.05 m) and the model values estimated from the east-dipping dislocation model are wide gray shaded bars. The solid arrow with 95% confidence ellipse shows the observed horizontal displacement of UGLE, the gray arrow is the model prediction. Surface projections of best-fit fault planes: the black rectangle corresponds to an east-dipping geometry (preferred); the dotted rectangle corresponds to a west-dipping geometry. The double lines mark the lower edge of the planes. Also shown is the Harvard CMT focal mechanism (parameters in Table 1) and the surface rupture.

Table 1. Parameters for the Fault From Inversion of GPS and Leveling Data with Constraints on Orientation, Location, and Dimension From Seismology

Length km	Width km	Dip °E	Strike °	Lat. °N	Lon. °E	Depth (centroid) km	Dip slip m ± 1 σ	Strike slip m ± 1 σ	Mo Nm × 10^{19}	M_w	WRSS
						Geodetic Inversion (E-dip)					
17.9	17.6	*51*	153.9	48.73	*142.20*	6.8	2.7 ±0.05	−0.4 ±0.13	2.56	6.94	158
						Geodetic Inversion (W-dip)					
26.0	31.3	*135*	*198*	48.68	142.34	11.1	1.9 ±0.04	0.5 ±0.30	4.68	7.11	697
						Harvard CMT					
E-dip		36	328	48.77	142.03	15	rake 60°		1.92	6.8	
W-dip		60	183				rake 110°				

Latitude and longitude refer to the center of the upper edge of the fault plane, and depth is to the fault plane center or to the moment tensor centroid. Positive dip slip is reverse and positive strike slip is right-lateral. Italics indicate parameters that were constrained in the inversion.

so 51° is a constrained value (Table 1). Also, the model would prefer a rupture that is located west of the mapped rupture trace. Thus, the longitude value is also constrained. If the fault is allowed to end below the surface, the preferred up-dip edge is at 3-km depth.

[15] The west-dipping model plane is similarly constrained to strike and dip within ±15° of the CMT nodal plane and to reach the surface. No constraints are imposed on its horizontal location, however, since models whose rupture trace is near the observed surface rupture are not able to produce even a resemblance of the observed uplift field. The inversion prefers dips less than 45° and strikes clockwise of 198°, which are the bounding values.

[16] The east-dipping model plane is preferred since it fits the data significantly better (factor of 4), it is more consistent with the aftershock distribution and the location of the surface rupture, and the resulting geodetic moment is closer to the seismically determined value. The largest misfit in vertical displacements is less than 0.2 m, and the measured and predicted horizontal displacement of UGLE agree within 0.002 m. The misfit could be further diminished by considering more than one fault plane and/or distributed rather than uniform slip. We believe, however, that the simple model with a limited number of variable parameters agrees reasonably well with the available observations.

5. Conclusions

[17] Significant, >1m, vertical displacements of 20 GPS stations caused by the August 4, 2000 Uglegorsk earthquake, were estimated by comparison of preseismic spirit leveling with postseismic GPS data. The constrained inversion of elevation changes provides evidence for a thrust-mechanism rupture on an east-dipping fault plane. The kinematics of this event is consistent with most well-determined seismic focal mechanisms for large earthquakes in Sakhalin (see *Seno et al.* [1996] for a summary), as well as the observed interseismic oblique-convergent velocity field across Sakhalin.

[18] **Acknowledgments.** This study was supported with NSF grants EAR 0106999, 0106002, and 0105587 to LDEO, UC Berkeley, and to MIT, respectively, and by JPL grant 1203235 and IRIS grant 311 to LDEO. Shawn Larsen and the anonymous reviewer provided many constructive suggestions which helped to improve the manuscript. Earthquake locations shown in Figure 1 are the NEIC/CNSS archived at the Northern California Earthquake Data Center (NCEDC). Figures were drawn with the GMT software [*Wessel and Smith*, 1998].

References

Bulgakov, R. F., A. I. Ivaschenko, Ch. U. Kim, K. F. Sergeev, M. I. Strel'tsov, A. I. Kozhurin, V. M. Besstrashnov, A. L. Strom, Y. Suzuki, H. Tsutsumi, M. Watanabe, T. Ueki, T. Shimamoto, K. Okumura, H. Goto, and Y. Kariya, Active faults in northeastern Sakhalin, *Geotectonics, 36, 227–246, Transl. from Geotektonika, 3*, 66–86, 2002. (Russ.)

Bürgmann, R., P. Segall, M. Lisowski, and J. Svarc, Postseismic strain following the 1989 Loma Prieta earthquake from GPS and leveling measurements, *J. Geophys. Res.*, *102*, 4933–4955, 1997.

Chapman, M. E., and S. C. Solomon, North American-Eurasian plate boundary in northeast Asia, *J. Geophys. Res.*, *81*, 921–930, 1976.

DeMets, C., A test of present-day plate geometries for northeast Asia and Japan, *J. Geophys. Res.*, *97*, 17,627–17,635, 1992.

Heki, K., S. Miyazaki, H. Takahashi, M. Kasahara, F. Kimata, S. Miura, N. F. Vasilenko, A. Ivashchenko, and K.-D. An, The Amurian plate motion and current plate kinematics in eastern Asia, *J. Geophys. Res.*, *104*, 29,147–29,155, 1999.

Kogan, M. G., G. M. Steblov, R. W. King, T. A. Herring, D. I. Frolov, S. G. Egorov, V. Y. Levin, A. Lerner-Lam, and A. Jones, Geodetic constraints on the relative motion and rigidity of Eurasia and North America, *Geophys. Res. Lett.*, *27*, 2041–2044, 2000.

Sandwell, D., and W. H. F. Smith, Marine gravity anomaly from Geosat and ERS 1 satelite altimetry, *J. Geophys. Res.*, *102*, 10,039–10,054, 1997.

Seno, T., T. Sakurai, and S. Stein, Can the Okhotsk plate be discriminated from the North American plate?, *J. Geophys. Res.*, *101*, 11,305–11,315, 1996.

Sergeev, K. F., Y. P. Nikitenko, V. A. Shulman, S. B. Zolotarskaya, V. K. Zakharov, V. P. Semakin, and G. G. Yakushko, Recent vertical crustal motion of Sakhalin, *Doklady Akademii nauk SSSR*, *257*, 202–204, 1981. (in Russ.)

Wessel, P., and W. H. F. Smith, New, improved version of Generic Mapping Tools released, *EOS, Trans. AGU*, *79*, 579, 1998.

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