The mechanism of postseismic deformation triggered by the 2006–2007 great Kuril earthquakes

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[1] In 2006–2007, a doublet of great earthquakes ($M_w > 8$) struck in the center of the Kuril subduction zone, a thrust event followed by an extensional event. Our observations of the Kuril GPS Array in 2006–2009 outline a broad zone of postseismic deformation with initial horizontal velocities to 90 mm/a, and postseismic uplift. We show that most of the postseismic signal after the great Kuril doublet is caused by the viscoelastic relaxation of shear stresses in the weak asthenosphere with the best-fitting Maxwell viscosity in the range of (5–10) × 10^{17} Pa s, an order of magnitude smaller than was estimated for several subduction zones. We predict that the postseismic deformation will die out in about a decade after the earthquake doublet. Our results suggest large variations among subduction zones in the asthenospheric viscosity, one of the most important rheological parameters.
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1. Introduction

[2] Transient surface deformation following great subduction earthquakes reflects the rheology of the lithosphere and sublithospheric mantle. In 2006, we installed the continuous GPS array KURILNET on islands of the Kuril subduction zone several months before a pair of great earthquakes (M_w of 8.3 and 8.1) struck in the central Kurils (Figures S1 and S2 of the auxiliary material).[1] The first earthquake was a thrust event on 15 November 2006, followed by an extensional event on 13 January 2007 [*Lay et al.*, 2009]. Hereafter these events are called the 2006 and 2007 earthquakes. Later, we added stations in the near field of earthquake ruptures.

[3] Three candidate mechanisms have been proposed to explain the postseismic surface motion: (1) viscoelastic relaxation [*Pollitz et al.*, 2008], (2) frictional afterslip [*Marone et al.*, 1991], (3) poroelastic rebound [*Peltzer et al.*, 1996]. Here we analyze postseismic deformation for 2.7 years after the great Kuril earthquakes in terms of viscoelastic relaxation and afterslip. We do not consider the poroelastic rebound because its effect is too small at distances from the hypocenter to the KURILNET stations.

2. GPS Data and Postseismic Surface Deformation

[4] The data were processed by the GAMIT/GLOBK software [*Herring et al.*, 2006]. Each daily solution combined observations at KURILNET and at 24 globally distributed IGS core stations; final IGS satellite orbits and the ITRF2005 reference frame were used. Surface deformation was modeled with respect to the overriding tectonic plate, on which the KURILNET stations are placed. We assumed that the Sea of Okhotsk (the overriding region) belongs to the North American plate [*Kogan and Steblov*, 2008]. We analyze station displacements over the intervals 2007.5–2008.5 and 2008.5–2009.5; the displacements were estimated by fitting a quadratic function to the daily postseismic time series over the interval 2007.5–2009.5 and then evaluating the positions at points 2007.5, 2008.5, and 2009.5 from the best fit function.

[5] Observed GPS displacements on the Kuril arc include the postseismic motion at a decreasing speed and the interseismic motion at a constant speed (Figure 1). The postseismic motion towards the ruptures of the 2006–2007 earthquakes prevails in the near field (stations URUP, KOST, KETC, MATC, and KHAC within ~200 km from the epicenters); the speed of postseismic deformation was to 90 mm/a over the period 2007.5–2008.5; the speed decreased by about 30% over the period 2008.5–2009.5. Interseismic deformation in the direction of subduction is caused by coupling at the subduction interface. This effect prevails at sites outside the rupture zone in the along-strike direction. The speed of the interseismic motion in the near field is unknown because GPS observations started after the earthquakes. We neglect this motion because the coupling is likely weak in the central Kurils [*Song and Simons*, 2003], so interseismic deformation will be the same size or smaller than observed along the rest of the arc.

[6] In the analysis of postseismic deformation, we mostly consider the effect of the 2006 Kuril earthquake. The surface deformation following the 2007 earthquake is relatively small because of its smaller size and shallow depth [*Ammon*

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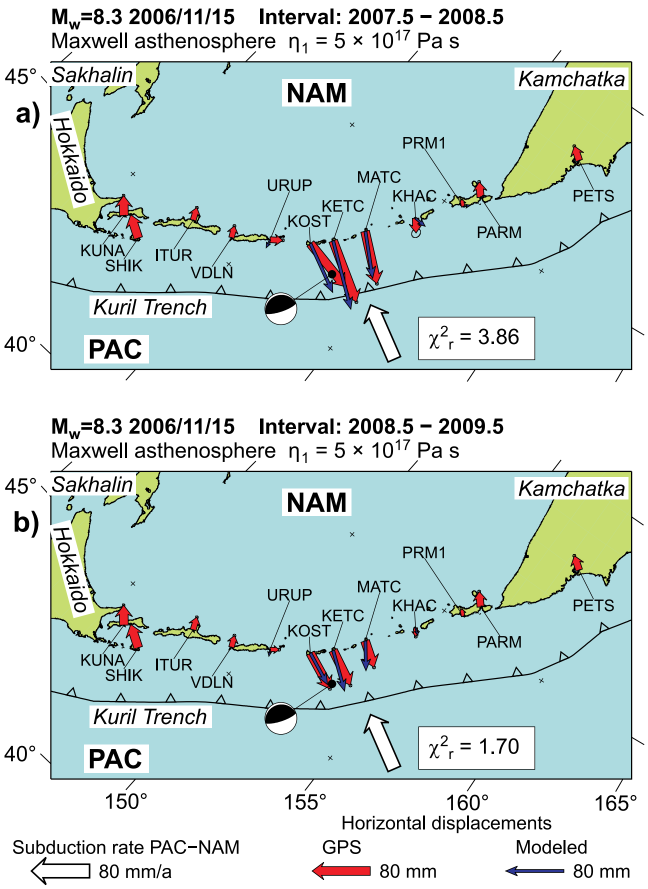

Figure 1. Observed and modeled horizontal postseismic displacements of GPS stations following the 2006–2007 Kuril earthquakes. The intervals are (a) 2007.5–2008.5 and (b) 2008.5–2009.5. The best-fitting model is estimated for viscoelastic relaxation triggered by the 2006 M_w = 8.3 Kuril earthquake. The postseismic motion prevails at stations URUP, KOST, KETC, MATC, and KHAC. The Kuril megathrust (barbed curve) and GPS stations (4-character identification) are denoted. PAC and NAM are the Pacific and North American plates, respectively. The GCMT beachball of the 2006 earthquake refers to the NEIC epicenter. Displacements with 1-σ error ellipses are estimated with respect to NAM. Observed displacements for stations KOST, KETC, and MATC were corrected for small (<5 mm) coseismic offsets from the 2009 M_w = 7.4 earthquake in the central Kurils. Misfit to the data from the models, reduced chi-square χ^2_r, was evaluated assuming the 1-σ error per model horizontal component as: 5 mm + abs(0.2 × displacement). Stations included in misfit: URUP, KOST, KETC, MATC, and KHAC.

et al., 2008], and because of its greater distance from the GPS stations.

3. Modeling of Horizontal Deformation

3.1. Viscoelastic Relaxation

[7] *Ammon et al.* [2008] suggested that the 2-month delay between both great Kuril earthquakes of 2006–2007 indicates a viscoelastic strain in the lithosphere. Here we consider the viscoelastic relaxation in the asthenosphere on a timescale of years, a fundamentally different process.

[8] We estimated postseismic motion with the VISCO1D software [*Pollitz et al.*, 2006]. The solution is presented as a spherical harmonic expansion of normal modes in a spherically stratified, self-gravitating, compressible, viscoelastic Earth, triggered by coseismic slip. For the 2006 earthquake, we used as an input the updated coseismic slip distribution of *Steblov et al.* [2008]; the rupture was modeled by three planes dipping 9, 16, and 22°, and the 8 × 3 grid was extended to 460 km along the strike.

[9] We chose the Earth model consisting of 68 layers, similar to that used by *Pollitz et al.* [2006] for the 2004 Sumatra earthquake. The elastic lithosphere is assumed to be 62-km thick in accordance with the flexural studies of the Pacific plate near the Kurils [*Levitt and Sandwell*, 1995]. For the asthenosphere (depths 62–220 km), we assumed the Maxwell rheology; we tested values of asthenospheric Maxwell viscosity η_1 in the range 10^{17} to 10^{20} Pa s, comparing predicted and observed postseismic motion over the time intervals 2007.5–2008.5 and 2008.5–2009.5. We also tested the Burgers rheology defined by the steady state viscosity η_1, varied in the same range as Maxwell viscosity, and the transient viscosity η_2 fixed to 5×10^{17} Pa s. Such a low η_2 was proposed by *Pollitz et al.* [2006] to match the first several months of postseismic motion after the 2004 Sumatra earthquake, although that time period probably includes afterslip [*Paul et al.*, 2007]. For the mantle below the asthenosphere, we assumed the Maxwell rheology and set η_1 to 10^{20} Pa s at depths 220–670 km and to 10^{21} Pa s at depths below 670 km.

[10] The best fit model of viscoelastic relaxation from the 2006 earthquake was found for the asthenospheric Maxwell viscosity $\eta_1 = 5 \times 10^{17}$ Pa s. Figure 1 compares GPS horizontal displacements with predictions of the best fit model. Both the slope and curvature of the observed motion are well reproduced (Figure 2). Predicted motions for Maxwell and Burgers rheologies differ by less than 5%, because the chosen time intervals start late with respect to the time of the earthquake (Figure S3 of the auxiliary material). Agreement between observations and the viscoelastic model rapidly deteriorates with increase in the tested viscosity (Figure S4).

[11] Viscoelastic relaxation of the 2007 earthquake was modeled using the coseismic slip model J7B of *Steblov et al.*

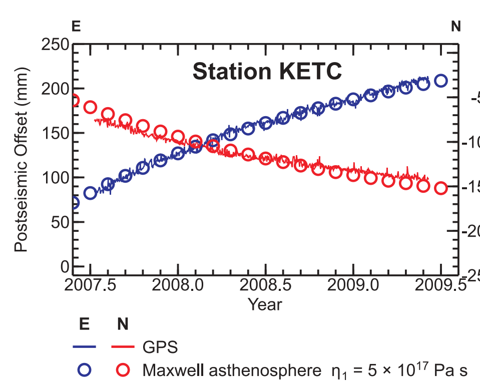

Figure 2. Postseismic time series of station KETC over the interval 2007.5–2009.5: Observed and predicted from viscoelastic relaxation. Maxwell rheology with viscosity $\eta_1 = 5 \times 10^{17}$ Pa s is assumed for the asthenosphere.

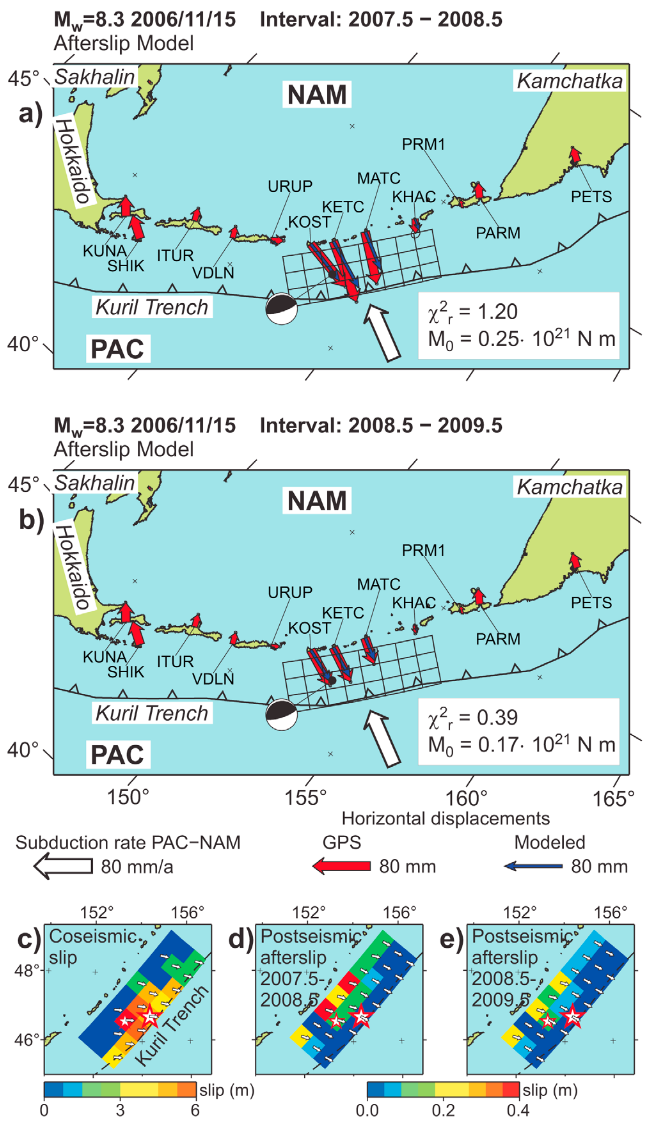

Figure 3. (a, b) Same as in Figure 1 but the best-fitting model is postseismic afterslip. (c–e) Inversions for coseismic slip and for afterslip on the rupture of the 2006 Kuril earthquake. Inversions were performed on the 8 × 3 grid. The 8-cell row nearest to the Kuril trench dips 9°, the middle 8-cell row dips 16°, and the 8-cell row farthest from the trench dips 22°. All dips are directed to NW. Large and small stars denote the GCMT centroid and NEIC epicenter locations, respectively.

[2008] with the 25 km downdip width of the rupture plane agreeing with the seismological inversion [*Ammon et al.*, 2008]. The contribution to the surface postseismic displacements is small compared with the 2006 earthquake (Figure S5).

[12] In this paper, we discuss only spherically symmetric layered Earth models, which can be treated by VISCO1D. The most prominent aspherical perturbation in rheology is the subducted lithospheric slab [*Hu et al.*, 2004; *Pollitz et al.*, 2008; *Suito and Freymueller*, 2009]. For the Sumatra 2004 earthquake, the predicted horizontal displacements of stations on the overriding plate were reduced by about 20% if the effect of the slab was included [*Pollitz et al.*, 2008]. To counteract the damping effect of the slab, the viscosity of the asthenosphere should be decreased compared with the model without the slab. An alternative way to compensate the effect of the slab is to reduce the thickness T_e of the elastic lithosphere [*Hu et al.*, 2004; *Pollitz et al.*, 2008]; however, the resulting increase in displacements is small as long as T_e is changed within its uncertainty, by about 10 km (Figure S6).

3.2. Afterslip

[13] Next, we test whether the horizontal postseismic deformation in the central Kurils can be explained by after-

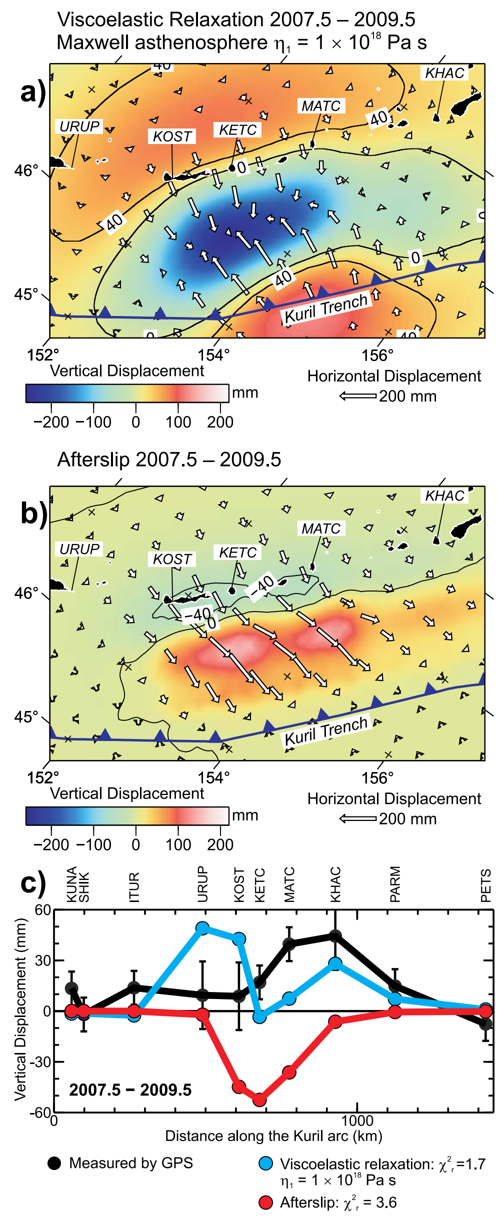

Figure 4. Surface postseismic displacement fields and a profile of postseismic vertical displacement from the 2006/11/15 Kuril earthquake. In all plots, total displacements over the interval 2007.5–2009.5 are shown. In Figures 4a and 4b, the vertical displacement field is shown in color with superimposed contours. (a) The best-fitting model of viscoelastic relaxation. (b) The best-fitting model of afterslip from inversion of GPS horizontal displacements. (c) Observed vertical displacements with 1-ó error bars and the best-fitting models from viscoelastic relaxation and from afterslip. GPS station identifications are shown on top.

slip on the coseismic rupture. We attribute GPS displacements to the 2006 event neglecting the smaller component due to the 2007 event; even if the afterslip moment for the 2007 event were twice as large as the coseismic moment, it would produce much smaller displacements (Figure S7). We do not parameterize afterslip from friction laws, but we directly invert GPS displacements over the intervals 2007.5–2008.5 and 2008.5–2009.5 for the slip distribution by constrained, nonlinear, damped least squares (Figure 3). We use in the inversion Green's functions estimated by the static version of VISCO1D for a spherical layered Earth model [*Steblov et al.*, 2008]. We assume the same three rupture planes, each divided into eight cells as in the coseismic inversion; the rake is constrained in the range 115°–125° as in the coseismic inversion.

[14] Predicted displacements in the central Kurils match GPS observations quite well for all stations, for both consecutive annual intervals (Figures 3a and 3b). Postseismic slip peaks on the deepest plane at depths 22–42 km in contrast to coseismic slip, which peaks on two most shallow planes at depths < 22 km (Figures 3c–3e).

4. Modeling of Vertical Deformation

[15] Our modeling shows that the horizontal deformation following the 2006 Kuril earthquake is explained equally well by either of two alternative mechanisms: viscoelastic relaxation or afterslip. A thrust earthquake, like the 2006 Kuril event, triggers vertical postseismic motion that can help distinguish between the competing deformation mechanisms [*Nishimura and Thatcher*, 2003] although the vertical GPS signal is less precise than the horizontal signal. For the 2006 earthquake, the best-fitting models of viscoelastic relaxation and of afterslip (based on the observed horizontal motions) predict quite different vertical motions (Figure 4). For the central Kuril Islands, viscoelastic relaxation requires uplift; in contrast, afterslip requires subsidence. The 2007.5–2009.5 GPS observations in the center of the Kuril subduction zone show postseismic uplift by as much as 40 mm in two years (Figure 4c). Viscoelastic relaxation for a Maxwell asthenosphere with viscosity $\eta_1 = 1 \times 10^{18}$ Pa s predicts general uplift of 0–40 mm in reasonable agreement with the data (reduced chi-square $\chi_r^2 = 1.7$), although the observed uplift is not reproduced in detail. In contrast, afterslip predicts general subsidence to 50 mm, completely incompatible with observations.

[16] For the 2007 earthquake, a model of viscoelastic relaxation predicts an insignificant vertical signal (compare Figures 4c and S7a); a model of afterslip predicts subsidence in contrast to the observed uplift (Figure S7b).

[17] A joint afterslip-viscoelastic model might prove to be a better fit than either mechanism separately, but viscoelastic relaxation would have to be the dominant component in such a case. Our estimate of the viscosity of the asthenosphere predicts that postseismic motion of stations in the near field of the 2006 earthquake will be reduced to <5 mm/a within a decade following this event (Figure S8 of the auxiliary material).

5. Conclusion

[18] Our preferred explanation of the postseismic deformation after the 2006–2007 Kuril earthquakes is viscoelastic relaxation. We infer a Maxwell viscosity in the asthenosphere of about 1×10^{18} Pa s, which is lower than for several other subduction zones [*Wang*, 2007]. Questions arise: Is this viscosity an effective value for the specific time period, as was found for several continental regions [*Freed et al.*, 2006; *Thatcher and Pollitz*, 2008]? Can the postseismic study of later period infer higher viscosity indicating power-law rheology?

[19] Several rock-mechanics and geodetic studies provide evidence that the viscosity inferred for the asthenosphere in this paper can be a steady state property. From laboratory studies, values of viscosity ranging from 1×10^{18} to 1×10^{19} Pa s agree with the rheology of rocks containing even small amounts of water [*Bürgmann and Dresen*, 2008]. Rapid glacial isostatic adjustment in the Cascadia subduction zone can be explained by the Maxwell asthenospheric viscosity of $\sim 3 \times 10^{18}$ Pa s [*James et al.*, 2009]. A similar viscosity, $(4–12) \times 10^{18}$ Pa s best explains post-Little Ice Age glacial isostatic adjustment in southeast Alaska [*Sato et al.*, 2011]. Studies of the 1964 Alaska earthquake and the 2002 Denali earthquake find values that are similar or about one order of magnitude larger [*Freed et al.*, 2006; *Johnson et al.*, 2009; *Suito and Freymueller*, 2009]. The Kuril arc is built on oceanic crust, and a lower viscosity suboceanic upper mantle may be more appropriate than the sub-continental mantle found in Cascadia and Alaska, potentially accounting for the difference in viscosity estimates. The very low mantle viscosity beneath the Kuril Islands may explain why viscoelastic relaxation dominates the postseismic response in this region, whereas afterslip appears to dominate in some other subduction zones.

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