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The Vertical Geodetic Signature of the Megathrust Earthquake Cycle

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It has been recognized since at least the seminal studies of Savage and Prescott (1978) and Thatcher and Rundle (1984) that viscous mantle flow plays an important role in the earthquake cycle by relaxing earthquake-induced stresses slowly over time and reloading the fault ahead of the next earthquake. Recent subduction zone studies have inferred relatively low effective mantle viscosities of order 10^{19} Pa s in the mantle wedge. This assertion of low viscosity is particularly important in the context of the earthquake cycle because viscosities of order 10^{19} Pa s correspond with short material relaxation times of order 10 years. If this viscosity is representative of the average mantle viscosity throughout the centuries-long earthquake cycle at some subduction zones, we would expect transient deformation to occur at all times of the earthquake cycle. We show the vertical deformation field is highly sensitive to mantle flow at subduction zones. To examine this, in southwest Japan, we tie together leveling, tide-gauge, and GPS data to produce a vertical velocity field spanning nearly 120 years of the earthquake cycle and capturing about 70 years of deformation following the Nankai/Tonankai earthquakes. We show that 2D viscoelastic earthquake cycles reproduce the observed vertical deformation field. Postseismic vertical velocities from 1947 to 2017 are explained well with 4 meters of imposed slip above 20 km on the interface, rate-strengthening afterslip on the interface between 20 and 45 km depth, and nearly 50 years of viscoelastic mantle flow with an average mantle viscosity of order 10^{19} Pa s. Present-day vertical velocities are similar to velocities from 1896-1934. In northern Japan, widespread subsidence of the eastern side of Honshu is observed in the present-day velocity field and in leveling data since year 1900 with the hinge line located ~100 km arcward of the bottom edge of the 2011 M9 rupture. The widespread subsidence requires transitional coupling in an elastic model down to 150 km depth, well within the mantle wedge. Alternatively, we show that the widespread subsidence is consistent with much shallower coupling (above 80 km depth) in 2D viscoelastic models of the earthquake cycle incorporating a subducting elastic slab and Maxwell viscoelastic mantle wedge and subducting mantle lithosphere. Repeated earthquakes on the shallow subduction interface are imposed and constant-stress creep is modeled at greater depths on the subducting interface. Wind find that mantle relaxation following large, infrequent M9-class earthquakes rupturing the upper part of the interface produces the observed widespread subsidence in northern Japan.