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Seismic versus aseismic slip: Probing mechanical properties of the northeast Japan subduction zone

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ABSTRACT

Fault slip may involve slow aseismic creep and fast seismic rupture, radiating seismic waves manifested as earthquakes. These two complementary behaviors accommodate the long-term plate convergence of major subduction zones and are attributed to fault frictional properties. It is conventionally assumed that zones capable of seismic rupture on the subduction megathrust are confined to between about 10 to 50 km depth; however, the actual spatiotemporal distribution of fault mechanical parameters remains elusive for most subduction zones. The 2011 Tohoku M_w 9.0 earthquake ruptured with >50 m slip up to the trench, thus challenging this conventional assumption, and provides a unique opportunity to probe the mechanical properties of the Japan subduction zone. Drawing on the inferred distribution of coseismic and postseismic slip, it has recently been suggested that portions of the megathrust are capable of switching between seismic and aseismic behavior. Kinematic models of the coseismic rupture and 15-month postseismic afterslip of this event suggest that the coseismic rupture triggered widespread frictional afterslip with equivalent moment magnitude of 8.17–8.53, in addition to viscoelastic relaxation in the underlying mantle. The identified linear relation between modeled afterslip, slip inferred from repeating earthquakes on the plate interface, and the cumulative number of aftershocks within 15 km distance of the subduction thrust suggests that most aftershocks are a direct result of afterslip. We constrain heterogeneous rate-state friction parameters of the subduction thrust from the computed coseismic stress changes and afterslip response. Our results indicate a variable pattern along dip and strike, characterizing areas down-dip and south of the main rupture zone as having velocity-strengthening properties. In agreement with seismic tomographic models of plate boundary elastic properties and geologic evidence for previous $M > 8.5$ megathrust earthquakes on this section of the plate boundary, we suggest that the obtained pattern of the frictional properties is characteristic of subducted material and thus persistent in time and space.

1. Introduction

Fault slip comprises seismic and aseismic components, which occur on patches with velocity weakening (VW) and velocity strengthening (VS) properties (Dieterich, 1978; Ruina, 1983), respectively. Traditionally, it is thought that VW properties characterize the depth range of 10 to 50 km on subduction zones, governed by material properties, fluid pressure and temperature (Pacheco et al., 1993). However, identifying the actual distribution and temporal evolution of patchworks of VW and VS behavior has proven challenging (Barbot et al., 2009; Perfettini et al., 2010; Shirzaei et al., 2013). For instance, portions of a fault that exhibit longer-term VS behavior, undergoing stable creep at low velocities comparable to tectonic rates, may alter their frictional behavior to VW (Noda and Lapusta, 2013; Reinen et al., 1991; Shibazaki et al., 2011) and experience fast dynamic rupture with slip rates of order of 1 m/s due to dynamic weakening effects (Noda and Lapusta, 2013). Moreover, the zones that are effectively locked during the interseismic period may contain patches of VS behavior slipping at low rates, which are held back by surrounding locked VW zones (Bürgmann et al., 2005). It has also been suggested that areas that previously ruptured in M 7–8 ruptures in the northeast Japan subduction zone slipped stably following the Tohoku earthquake (Johnson et al., 2012). Thus identifying the spatial extent and temporal evolution of VW and VS properties on the

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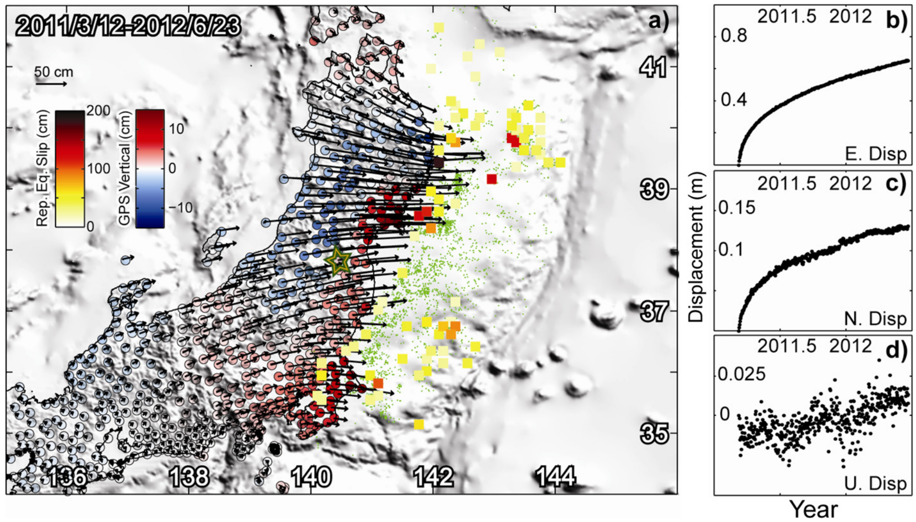

Fig. 1. (a) The cumulative 3D surface deformation measured with continuous GPS observations during 15-month postseismic period (arrows and colored circles onshore) [source: Geospatial Information Authority of Japan]. The distribution of aftershocks during this period is shown by green dots [source: F-net Japan broadband seismograph network]. The colored squares offshore indicate groups of repeating earthquakes (Uchida and Matsuzawa, 2013). Each circle is color-coded by the equivalent cumulative postseismic creep from 3 days after the mainshock through June 23, 2012, (b–d) examples of time series of the 3D postseismic displacement at a selected GPS station, marked by green star in panel (a), eastward and northward displacements are considered as positive. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

off-Tohoku subduction zone is of great importance for studying the mechanics of the megathrust and its seismic potential.

The M_w 9.0 Tohoku earthquake occurred on March 11, 2011 on the megathrust where the Pacific plate subducts west-northwestward under the Okhotsk plate at an average rate of ∼8 cm/yr (Apel et al., 2006). An important aspect of the rupture models of this event is that slip of ∼50 m occurred in the shallowest sections of the subduction zone near the Japan trench (Fig. S1), confirmed by repeated bathymetric (Fujiwara et al., 2011) and seismic reflection data showing large offsets up to the trench (Kodaira et al., 2012). This unexpected large shallow slip caused a destructive large tsunami (Simons et al., 2011) and surprised the scientific community and authorities (Sagiya et al., 2011). This extraordinary behavior is rooted in the particular mechanical properties characterizing the zones of VW and VS behavior (Dieterich, 1978; Ruina, 1983).

The co- and postseismic observations of the deformation associated with this event, provide a unique opportunity to study the spatiotemporal distribution of fault mechanical parameters in a seismically active region (Johnson et al., 2012; Ozawa et al., 2012, 2011; Pollitz et al., 2011; Simons et al., 2011). The postseismic deformation, driven by the stress imparted during coseismic rupture (Bürgmann and Dresen, 2008), comprises afterslip on the megathrust, viscoelastic relaxation of the volume surrounding the fault and poroelastic rebound. Here, we investigate Global Positioning System (GPS) time series spanning the first 15 months of the surface deformation following the event (Fig. 1), complemented with direct observation of the creep on the megathrust interface obtained using characteristic repeating earthquakes (CREs) (Uchida and Matsuzawa, 2013). The combination of these two data sets allows us to illuminate the kinematics of the afterslip and probe the spatial distribution of rate-state frictional properties on the subduction plate interface of NE Japan.

2. Data

The co- and postseismic observations of the 3D deformation associated with the Tohoku earthquake are recorded at more than 1000 continuous and campaign GPS stations (Ozawa et al., 2012). The GPS time series are provided by the Geospatial Information Authority of Japan. Here, we focus on the cumulative 3D surface deformation measured during the initial 15-month postseismic period (see Fig. 1 and supplementary movies). The postseismic GPS time series (Ozawa et al., 2012) are characterized by a rapidly decaying pattern seen in postseismic deformation elsewhere (Bürgmann and Dresen, 2008; Hsu et al., 2006; Perfettini and Avouac, 2007). The vertical deformation shows zones of uplift along the Pacific coast, whereas the far coast is characterized by subsidence (Fig. 1a).

We also explore characteristic repeating earthquakes (CREs). The CREs are events on the plate interface that have nearly identical waveforms and that have coincident hypocenters to resolutions of a few 10s of meters (Uchida and Matsuzawa, 2013). Because of these attributes, a time-ordered sequence of repeating events is believed to represent repeated failures of the same small fault patch, loaded by aseismic slip on the surrounding fault surface (Nadeau and Johnson, 1998; Schaff et al., 1998). Events in a group of CREs have recurrence intervals that generally vary in proportion to the inverse of the creep rate on the fault where the repeating earthquakes are located, indicating that they act as creepmeters directly installed on the fault interface. Thus, the location, magnitude and recurrence interval properties of the sequences can be used to infer the spatial and temporal distribution of deep aseismic slip (Nadeau and Johnson, 1998; Schaff et al., 1998). The cumulative slip obtained from post-Tohoku earthquake measurements of CREs (Fig. 1a) indicates no resolvable afterslip within the primary co-seismic rupture area and that the inferred postseismic creep surrounds the coseismic rupture and exhibits a temporal decay similar to that seen in the GPS data (Uchida and Matsuzawa, 2013).

3. Time-dependent afterslip model

To model the postseismic deformation of the first 15 months we consider three scenarios (Fig. 2), assuming the observed deformation resulted from afterslip on the subduction thrust fault buried in an elastic half-space medium and; (a) no viscoelastic relaxation is involved, (b) the viscoelastic relaxation occurs in a layered viscoelastic medium, (c) the viscoelastic relaxation occurs in a 3D layered viscoelastic medium that includes an elastic slab and higher-viscosity mantle below the Pacific-plate lithosphere. In the latter two cases, the optimum contribution