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Interactions between strike-slip earthquakes and the subduction interface near the Mendocino Triple Junction

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ABSTRACT

The interactions between the North American, Pacific, and Gorda plates at the Mendocino Triple Junction (MTJ) create one of the most seismically active regions in North America. The earthquakes rupture all three plate boundaries but also include considerable intraplate seismicity reflecting the strong internal deformation of the Gorda plate. Understanding the stress levels that drive these ruptures and estimating the locking state of the subduction interface are especially important topics for regional earthquake hazard assessment. However owing to the lack of offshore seismic and geodetic instruments, the rupture process of only a few large earthquakes near the MTJ have been studied in detail and the locking state of the subduction interface is not well constrained. In this paper, first, we use the second moments inversion method to study the rupture process of the January 28, 2015 M_w 5.7 earthquake on the Mendocino transform fault that was unusually well recorded by both onshore and offshore strong motion instruments. We estimate the rupture dimension to be approximately 6 km by 3 km corresponding to a stress drop of ∼4 MPa for a crack model. Next we investigate the frictional state of the subduction interface by simulating the afterslip that would be expected there as a result of the stress changes from the 2015 earthquake and a 2010 M_w 6.5 intraplate earthquake within the subducted Gorda plate. We simulate afterslip scenarios for a range of depths of the downdip end of the locked zone defined as the transition to velocity strengthening friction and calculate the corresponding surface deformation expected at onshore GPS monuments. We can rule out a very shallow downdip limit owing to the lack of a detectable signal at onshore GPS stations following the 2010 earthquake. Our simulations indicate that the locking depth on the slab surface is at least 14 km, which suggests that the next M8 earthquake rupture will likely reach the coastline and strong shaking should be expected there.

1. Introduction

The classic synoptic frictional model of a subduction zone thrust fault from top to bottom involves three-layers (Scholz, 1998; Obara and Kato, 2016) where the top rate-strengthening layer coincides with the accretionary wedge and has important implications for tsunami generation; the middle rate-weakening layer, often referred to as the locked zone during the interseismic period, fails during great megathrust earthquakes; and the bottom rate strengthening layer creeps stablely as afterslip following great earthquakes and continuously during the interseismic period, it also slips episodically during ETS events. The two transition zones between velocity weakening and strengthening often produce tremor and slow slip events that relieve small amounts of stress regularly (Scholz, 1998). In terms of earthquake hazard assessment, determining the spatial variations in the locking state on the interface and the downdip and updip limits of the locked zone are important for estimating the potential rupture areas of future earthquakes.

In the Cascadia subduction zone (CSZ), the spatial variations in interseismic locking and particularly the downdip and updip limits of the locked zone remain unclear. The low rate of interplate earthquakes (Obana et al., 2015; Morton and Bilek, 2015) and the uplift of the West Coast (McCaffrey et al., 2007) indicate the interface is largely locked at depths shallower than 20 km. Several studies have inverted geodetic data for the spatial distribution of the locking along the interface (McCaffrey et al., 2000, 2007; Burgette et al., 2009; Schmalzle et al., 2014; Pollitz and Evans, 2017). However, owing to the lack of offshore geodetic observations, there is little resolution of locking near the trench. Moreover, different modeling assumptions can produce significantly different results even in the

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10–30 km depth range where great earthquake slip is expected to be largest (Schmalzle et al., 2014; Pollitz and Evans, 2017). While in general episodic tremor and slow slip may mark the updip and downdip margins of the locked zone (Obara and Kato, 2016), in Cascadia, there may be a large spatial gap between the downdip edge of the locked zone and the well constrained tremor region (Liu, 2013). Additionally, no studies have yet reported transient slip or low frequency earthquake at the updip edge of the locked zone, e.g., within the accretionary wedge, adding to the uncertainty of the locking state near the trench (Wang and Tréhu, 2016).

Near the MTJ, the locking state of the southernmost part of the megathrust interface has only been estimated in the two most recent geodetic inversion studies (Schmalzle et al., 2014; Pollitz and Evans, 2017). The locking fraction in the models of Schmalzle et al. (2014) ranges from ~0.5 to ~1.0 depending on the regularization and other assumptions. Similarly, the locking rate in the models of Pollitz and Evans (2017) ranges from 0 to 30 mm/yr in models with different assumed rheologies for the surrounding region. Thus it remains an important goal to better constrain the expected rupture area in this region where the great earthquake recurrence interval is the shortest among the various segments along the Cascade megathrust (Goldfinger et al., 2008).

The goal of this paper is to evaluate an alternative method for probing the locking state on the subduction plate which takes advantage of the frequent moderate earthquakes on the nearby faults in the MTJ region. These earthquakes will cause Coulomb stress changes that could possibly generate transient aseismic fault slip, typically referred to as afterslip, on the thrust interface (Wallace et al., 2016). Afterslip is very common following large subduction earthquakes and delineates parts of the fault with velocity strengthening friction (Perfettini and Ampuero, 2008). Geodetic recordings of afterslip have been used to probe the frictional state of fault interface by analyzing its temporal evolution (Miyazaki et al., 2004; Hsu et al., 2006; Thomas et al., 2017). Similarly, velocity strengthening regions of crustal faults are often observed to undergo triggered afterslip following nearby earthquakes resulting from both static and dynamic stress changes (M. Wei et al., 2015). We determine the rupture area of a M_w 5.7 earthquake on the Mendocino transform fault and use the coseismic slip distribution from it and an intraplate earthquake within the subducting Gorda plate to calculate Coulomb stress changes on the thrust interface. We then simulate the afterslip and corresponding displacement signals at onshore GPS sites. We model different downdip limits of the locking zone and compare the simulated GPS series with the GPS observations to estimate a minimum depth of the downdip limit of the locking zone near MTJ.

2. Data and resources

Two earthquakes near MTJ are used as sources that generate stress perturbations on the slab surface. They are the Jan 10, 2010 M_w 6.5 earthquake and the Jan 28, 2015 M_w 5.7 earthquake (Fig. 1). The 2010 earthquake is the only earthquake that has a published finite fault inversion model near MTJ since the 1992 M_w 7.1 Cape Mendocino earthquake (Wei and McGuire, 2014; Rollins and Stein, 2010). We use the coseismic slip model from Wei and McGuire (2014) for the 2010 earthquake. For the 2015 earthquake, we apply the second moments inversion method (McGuire, 2004) to determine its rupture area and simulate it with a simple uniform slip model.

The M_w 5.7 earthquake occurred at 21:08:53, January 28, 2015 UTC about 27 km offshore at on the Mendocino transform fault (see Table 1 and IRIS Event Page, http://ds.iris.edu/ds/nodes/dmc/tools/event/5003592). The earthquake was recorded by a dense onshore/offshore seismic array with 45 stations within 80 km of the epicenter (Fig. 1). The offshore stations were from the Cascadia Initiative (CI network) Year 4 experiment (Toomey et al., 2014) that contained 20 stations with ocean bottom seismometers (OBS) from the Lamont–Doherty Earth Observatory (LDEO), the Scripps Institution of Oceanography (SIO) and the Woods Hole Oceanographic Institution (WHOI). The LDEO and SIO stations were broadband OBSs sampled at 125 Hz and 100 Hz respectively. The WHOI stations were equipped with both a broadband OBS and a strong motion accelerometer (Fig. 2) sampled at 50 Hz. The onshore stations were from the Northern California Seismic Network (NCSN), the Plate Boundary Observatory (PBO) and a temporary deployment of IRIS-Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL) sensors. 3 stations from the NCSN had both broadband seismometers and accelerometers installed; the 6 stations from the PBO were short period borehole seismometers and the 10 stations from PASSCAL are short period temporary stations. Offshore, the strong ground motions were recorded on scale by the 9 WHOI ocean bottom accelerometers and a few broadband OBSs located >30 km from the epicenter (Fig. 3). Onshore, the strong ground motion waveforms were only recorded on scale by the 3 NCSN accelerometers and the 6 PBO borehole seismometers while the other PASSCAL and NCSN broadband and short-period seismometers were clipped.

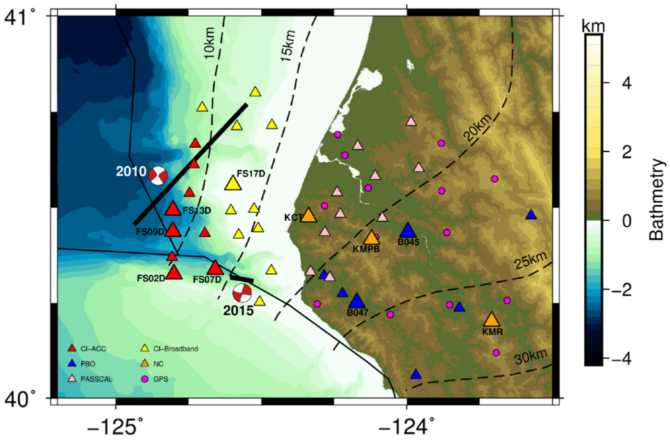

Fig. 1. Map of the study area near the MTJ. Triangles are seismic stations. Offshore stations are from Cascadia Initiative experiment with yellow triangles representing broanband OBS from LDEO and SIO and red triangles representing broadband and accelerometer stations from WHOI. Onshore, orange triangles are broadband and accelerometer stations from the NCSN, pink triangles are short-period stations from PASSCAL, blue triangles are borehole short-period stations from the PBO and magenta circles are GPS stations from the PBO. Stations used in the second moments inversion are shown by larger triangles with station names labeled. Bold black straight lines and beach balls denote location and Global CMT mechanisms of the 2010 and 2015 earthquakes (ANSS (Advanced National Seismic System) Composite Catalog event ID numbers are 71338066 and 72387946 for 2010 and 2015 earthquakes). Dashed lines show subduction slab depth contours (McCrory et al., 2012). Solid black lines are plate boundaries between Pacific, Gorda and North America plates from USGS Tectonic Plate Boundaries. Topography data is from NOAA. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Information of 2015 earthquake.

Time (UTC)	Lat/Lon	Depth	Strike/Dip/Rake
2015-01-28 21:08:53	40.3178°N 124.6067°W	17.2 km	Plane 1: 105°/87°/178° Plane 2: 194°/85°/9°

3. Second moments inversion

3.1. Method

The second moments of an earthquake's rupture are the second order space and time moments of the normalized moment-rate