Earth and Planetary Science Letters 419 (2015) 187–198

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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Numerical modeling of long-term earthquake sequences on the NE Japan megathrust: Comparison with observations and implications for fault friction

Nadaya Cubas [a,*,1], Nadia Lapusta [a,b], Jean-Philippe Avouac [a], Hugo Perfettini [c]

[a] Division of Geological and Planetary Sciences, California Institute of Technology, 1200 E. California Blvd, Pasadena, CA 91125, USA
[b] Division of Engineering and Applied Science, California Institute of Technology, 1200 E. California Blvd, Pasadena, CA 91125, USA
[c] Institut de Recherche pour le Développement, ISTerre, Grenoble, France

ARTICLE INFO

Article history:
Received 20 November 2014
Received in revised form 28 February 2015
Accepted 3 March 2015
Available online 20 March 2015
Editor: P. Shearer

Keywords:
Tohoku-Oki earthquake
thermal pressurization
shallow propagation
2D dynamic simulations of earthquake cycle

ABSTRACT

We use numerical modeling to investigate fault properties that explain key features of the 2011 Mw 9.0 Tohoku-Oki earthquake as well as the overall regional behavior of the NE Japan megathrust. In particular, we study the possibility that slip near the trench resulted from thermal pressurization on a shallow patch of the megathrust, and investigate whether low-velocity friction on that patch is rate-strengthening or rate-weakening. Our models also contain a deeper rate-weakening patch, not prone to efficient thermal pressurization, to account for the moderate-sized interplate seismicity. We produce earthquake sequences and aseismic slip in our models using 2D dynamic simulations that incorporate shear-induced temperature variations and the associated change in pore fluid pressure to capture thermal pressurization. We find that all our models can reproduce more frequent deeper moderate (Mw 7.5) events and less frequent larger events with substantial slip at shallow depth, as observed along the Fukushima–Miyagi segment of the Japan megathrust. However, only the scenario with a sufficiently rate-strengthening patch can match the thousand-year recurrence time of Tohoku-Oki-like earthquakes suggested by the historical and geological record, due to co-existence of seismic and aseismic slip at the shallow depths. This scenario also reproduces other characteristics of the Tohoku-Oki earthquake: the trenchward-skewed distribution of slip, the backward re-rupture of the deeper patch, as well as the weaker radiation at high frequency of the shallower portion of the rupture in spite of its larger slip.
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1. Introduction

The 2011 Mw 9.0 Tohoku-Oki earthquake produced exceptionally large shallow slip, at depth between 10 and 20 km, generating a major tsunami (Yamagiwa et al., 2015; Bletery et al., 2014; Wei et al., 2012; Ozawa et al., 2011; Ide et al., 2011; Simons et al., 2011; Ito et al., 2011) (Fig. 1a). The rupture propagated all the way to the trench, with the shallow-portion displacement of 15 to 40 m as attested from the displacement of ocean-bottom pressure gages (Ito et al., 2011) and comparison of bathymetric profiles measured in 1999 and after the earthquake in March 2011 (Fujiwara et al., 2011).

This large shallow slip is most surprising since (1) the upper portion of the megathrust is commonly thought to slip aseismically (e.g., Byrne et al., 1992; Oleskevich et al., 1999), (2) previous magnitude 7.5 earthquakes had only been instrumentally recorded along the deeper portion of the megathrust (Fig. 1b), and (3) interseismic strain accumulation models were not showing any evidence for locking of the megathrust at shallow depth (Hashimoto et al., 2009; Loveless and Meade, 2011). It should be noted, however, that the creep at shallow depth inferred from the interseismic models (Hashimoto et al., 2009; Loveless and Meade, 2011) was essentially due to the assumed initial condition and lack of resolution near the trench of the onshore geodetic data used in these inversions (Loveless and Meade, 2011).

Fig. 1a shows the co-seismic and afterslip models of Yamagiwa et al. (2015) derived from the modeling of on-shore and seafloor displacements. The co-seismic model is similar to the models obtained by other groups incorporating seismological and tsunami waveforms (e.g., Bletery et al., 2014), which all show that the rupture propagated close to the trench. The deeper patch of afterslip

* Corresponding author.
E-mail address: nadaya.cubas@upmc.fr (N. Cubas).
[1] Now at Institut des Sciences de la Terre, Université Pierre et Marie Curie, UMR 7193, 4 Place Jussieu, 75005 Paris, France.

http://dx.doi.org/10.1016/j.epsl.2015.03.002
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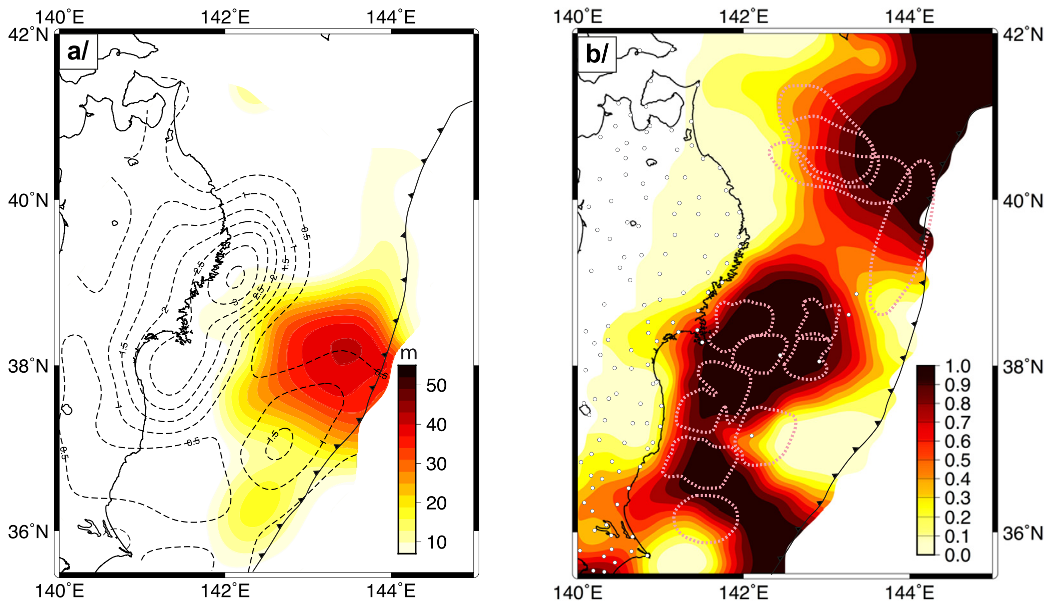

Fig. 1. (a) Coseismic (colors) and postseismic (black dashed lines) slip from Yamagiwa et al. (2015) derived from the modeling of on-shore and seafloor displacements. (b) Interseismic coupling ratio (colors) from an updated inversion of onshore and offshore geodetic measurements based on Perfettini and Avouac (2014) but including the interseismic seafloor displacements of Sato et al. (2013). Comparison of the observed and predicted displacements is given in the supplementary figure. The dotted pink contour lines show the estimated location of rupture areas of smaller (∼M7.5) historical earthquakes (Yamanaka and Kikuchi, 2004; Shibazaki et al., 2011; Johnson et al., 2012). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

outlines the downdip end of the co-seismic rupture as observed by previous studies (Ozawa et al., 2012; Johnson et al., 2012; Sun et al., 2014; Hu et al., 2014). There is some degree of uncertainty regarding the exact amount of slip that occurred near the trench due to the fact that the postseismic seafloor measurements were acquired weeks after the mainshock. Eastward displacement and subsidence at station FUKU, south of the rupture area, clearly indicate shallow afterslip there. In contrast, the postseismic seafloor displacements are mostly westward above the rupture area and indicate a predominantly viscoelastic relaxation process there, over the time period covered by these measurements, from one month to three years after the mainshock (Sun et al., 2014; Watanabe et al., 2014; Hu et al., 2014). The data does not rule out the possibility of shallow afterslip but the afterslip would need to be small enough to be obscured by the viscoelastic response over this time period. As suggested by Perfettini and Avouac (2014) (see their Section 6.3 and Appendix A1), some significant shallow afterslip could have occurred over the first month. The afterslip model of Yamagiwa et al. (2015) shows both deep and shallow afterslip mostly complementary to the co-seismic rupture area. It should be noted that this afterslip model, similarly to others (e.g., Ozawa et al., 2012), assumes no slip at the trench as a boundary condition in the inversion. Shallow afterslip could be underestimated as a result of this boundary condition and of the Laplacian regularization.

An interseismic coupling model before the Tohoku-Oki event is shown in Fig. 1b. It is a revised version of the model given in Fig. 11 of Perfettini and Avouac (2014). In this revised version, the interseismic seafloor displacements of Matsumuto et al. (2008) were replaced by the more recent measurements of Sato et al. (2013). These measurements, initially given relative to the North American plate, are referenced to NE Honshu assuming the NUVEL-1A plate motion of North America relative to Eurasia and the block motion of NE Honshu relative to Eurasia of Loveless and Meade (2011). We have considered two boundary conditions: one for which back-slip is prohibited near the trench (corresponding to a creeping trench at the long term slip rate prior to the mainshock, dabbed CT in the following), and another one for which back-slip rate at the trench is unconstrained (corresponding to a partially to fully locked trench prior to the mainshock, dabbed LT in the following). The two resulting inverted models yield nearly identical coupling maps, with the corresponding reduced chi-square values being 9.82 and 9.76, respectively; the LT model is shown in Fig. 1b. The LT model matches the data slightly better than the CT model because it has more degrees of freedom. The comparison of observed and predicted displacements and residuals are shown in the supplementary material.

Therefore, the seafloor measurements as reported in Sato et al. (2013) require some amount of interseismic creep near the trench. This implies that the locked patches below are apparently not screening the interseismic loading as would be expected from the stress shadow effect (Bürgmann et al., 2005; Hetland and Simons, 2010). Note that the historical ruptures are all located in the highly coupled area, with the exception of the 1896 Sanriku tsunami earthquake (Fig. 1b). It thus seems that the shallow portion of the Japan megathrust could creep aseismically, e.g. as afterslip and interseismically, as well as accumulate substantial slip during large tsunamigenic earthquakes.

The Tohoku-Oki earthquake is remarkable in two other ways. The large shallow slip area did not radiate much seismic energy at high frequencies compared to the deeper portion of the megathrust which experienced less slip (Ide et al., 2011; Simons et al., 2011; Meng et al., 2011; Wei et al., 2012). A complex propagation was also observed, with a small initial phase of deep rupture up to 40 s, followed by extensive shallow rupture at 60–70 s, and a continuing deep rupture lasting over 100 s (Ide et al., 2011). Finally, from tsunami records (Sawai et al., 2012), the last earthquake in the area with comparable tsunami deposits occurred in AD 869 and hence the recurrence time of the Tohoku-Oki-like events is probably ∼1000 years, unless the recurrence interval is quite irregular.

To reconcile these observations, Noda and Lapusta (2013) have suggested that the shallow megathrust could undergo aseismic slip at low slip rates, due to its rate-strengthening properties, as well as substantial coseismic slip due to efficient weakening by thermal pressurization of pore fluids (Sibson, 1973; Lachenbruch, 1980; Mase and Smith, 1985, 1987; Rice, 2006). From model parameters based on lab experiments (Tanikawa and Shimamoto, 2009), they were able to reproduce the larger slip of the shallow

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