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Fluid transport properties in sediments and their role in large slip near the surface of the plate boundary fault in the Japan Trench

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ABSTRACT

Fluid transport properties such as permeability and porosity are significant parameters that affect earthquake generation. We measured the transport properties of shallow sediments sampled around the plate boundary near the Japan Trench during IODP Expedition 343 at confining pressures up to 40 MPa. The permeabilities of samples from the shallow plate boundary fault were very low at 10^{-20} m^2, equivalent to a hydraulic diffusivity of 10^{-10} $m^2\,s^{-1}$. Permeability and porosity in the core of the fault zone at the plate boundary were lower than those in the immediately overlying sediments and the surrounding intact sediment, suggesting that the plate boundary fault can act as a barrier for fluid flow. Low permeability and high pore compressibility in the shallow plate boundary fault create a strong potential for dynamic fault weakening due to fluid pressurization with frictional heating, even when the initial shear stress is low. Our investigation supports the hypothesis that thermal pressurization on the fault plane helped facilitate the extremely large slip in the shallow part of the subduction zone during the Tohoku earthquake. As the fault zone has a lower permeability than the surrounding sediments and a higher clay content, pore pressure generation at depth by dehydration of clay minerals can explain formation of the shallow strong patch on the fault more reasonably than continuous fluid influx from the subducting oceanic crust, which does not affect pore pressure at depth in the fault zone. Although there are many possible mechanisms of fault weakening, thermal pressurization can act relatively efficiently as slip begins, even at shallow depths. Therefore our results support the role of thermal pressurization in shallow slip during the Tohoku earthquake.

1. Introduction

The 2011 Tohoku earthquake (*Mw* 9.0) broke the entire depth range of the seismogenic region of the plate interface between the subducting Pacific Plate and Honshu Island, Japan, and produced huge coseismic slip over the entire rupture area. The great slip deformation of the shallow trenchward edge of the rupture zone generated a tremendous tsunami (Ito et al., 2011). Kinematic inversion studies have found that a maximum slip greater than 50 m occurred near the trench (e.g., Ide et al., 2011; Yue and Lay, 2011), and bathymetric data and tsunami waveform inversion analysis indicate that significant coseismic slip reached parts of the trench during the event (Fujiwara et al., 2011; Fujii et al., 2011). The slip velocity on the fault plane exceeded 1 $m\,s^{-1}$ over a large area of shallow slip (Suzuki et al., 2011).

Experimental results of rate- and state-dependent friction (Dieterich, 1979) suggested that fault material in shallow parts of the plate boundary should show velocity-strengthening frictional behavior and favor aseismic slip (Saffer and Marone, 2003; Ikari et al., 2007). Numerical simulations have implied that velocity-strengthening friction also may act as a barrier to rupture propagation (Kato, 2008). However, tsunami deposits and historical documents indicate that there were great earthquakes of $M > 8$ off the coast of the Miyagi district of Honshu in the ninth century (Minoura et al., 2001). The 1896 Sanriku earthquake was probably a thrust near the trench with very large slip (Tanioka and Seno, 2001). In addition, historical observations of seismicity suggested that giant earthquakes could occur along the subduction zone in northeastern Japan (Kanamori et al., 2006).

Several mechanisms have been proposed to explain the giant earthquake in the Tohoku area (Mitsui and Iio, 2011; Kato and Yoshida, 2011; Mitsui et al., 2012a, 2012b). Kato and Yoshida (2011) simulated the recurrence of rare giant earthquakes and frequent large earthquakes by assuming a persistent strong patch and a large characteristic slip distance *Dc* in friction law on the shallow plate interface. The existence of a shallow strong patch was explained by a relatively low effective normal stress with generation

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of high pore pressures restricted to the deeper portion of the plate interface. They assumed a continuous influx of fluid from the deep crust into a low-permeability fault zone to cause the high pore pressure in the fault zone. Dehydration reactions of smectite transformation and opal-to-quartz transformation also can generate pore pressure at depth on the plate boundary (Spinelli and Saffer, 2004; Saffer et al., 2008). The hypothesis of Kato and Yoshida (2011) is consistent with the very low shear stress of 21 to 22 MPa at the plate interface of the Tohoku earthquake rupture zone estimated from stress tensor inversion by Hasegawa et al. (2011). Low friction at the plate boundary in NE Japan was also reported by Wang and Suyehiro (1999), who assumed a low friction coefficient of 0.03 to explain the compressional stress of the continental crust in Japan. The presence of a subducted seamount enhances the plate coupling that produces the velocity-weakening regime, but does not explain the large slip near the trench (Duan, 2012).

Mitsui et al. (2012a) proposed that another process, dynamic fault weakening by thermal pressurization due to frictional heating in the shallow part of the plate boundary, can influence slip behavior in a way similar to shallow strong patches. In both models, fluid transport properties as well as friction properties on the plate boundary fault are key parameters of earthquake scenarios. Lacking physical fluid transport property data, Mitsui et al. (2012a) relied on previously published data from a representative active fault. However, published fluid transport properties from fault zones have varied widely according to host rocks and tectonic settings (Noda and Shimamoto, 2005; Mizoguchi et al., 2008; Tanikawa et al., 2009) as well as pressure and temperature conditions (Wibberley, 2002; Faulkner and Rutter, 2000). Pore compressibility and specific storage in porous media have a strong influence on the pore pressure response through poro-elastic deformation (Wang, 2000), although these parameters for fault rocks are not well known (Wibberley and Shimamoto, 2003; Tanikawa et al., 2009).

The Japan Trench Fast Drilling Project (JFAST) (the Integrated Ocean Drilling Program (IODP) Expedition 343; Mori et al., 2012) drilled across the plate boundary fault near the Tohoku earthquake rupture a few kilometers landward of the Japan Trench. One goal of JFAST was to understand the dynamics of large slip on the shallow fault by collecting physical property data from core samples. Another goal was to identify a temperature anomaly around the slip zone to constrain the shear stress on the fault (or friction coefficient) during seismic slip. The project succeeded in coring highly sheared clay from the plate boundary fault at 820 meters below the seafloor (mbsf) and surrounding sediment material in the hangingwall and footwall.

In this paper, we report laboratory measurements of the transport properties of JFAST core samples. We also provide estimates of the probability of dynamic fault weakening due to pore-fluid pressurization based on a simple one-dimensional diffusion analysis incorporating the measured transport properties. Finally, we discuss the possible mechanisms that caused large slip at the shallow plate boundary during the Tohoku earthquake.

2. Experimental procedure

2.1. Sample information

Our laboratory tests used core samples from 689 to 827 mbsf (Table 1, lithologic Unit 3 to Unit 5, Chester et al., 2012) at JFAST site C0019 in the Japan Trench (Figs. 1a, 1c). Core and logging data pointed to two major faults at 720 and 820 mbsf. The core sample from the 820 m fault zone is very likely from the plate boundary, which is very narrow with less than 5 m thickness, as described in Chester et al. (2012). Fractures were visible to the naked eye in samples from 810 and 817 mbsf, suggesting the development of a fracture zone near the core of the fault.

Table 1
Core section information and fluid transport properties at in-situ depth of core samples shown in Fig. 3.

Core section (unit)	Top of sample (cm)	Bottom of sample (cm)	Depth below seafloor (mbsf)	Normal stress (MPa)	Permeability (m^2)	Porosity	Specific storage (Pa^{-1})	Hydraulic diffusivity ($m^2\,s^{-1}$)	Grain density ($g\,cm^{-3}$)	Run number	Pre-loading
4R-1	88	90	689.4	4.67	4.68E−19	–	–	–	2.51	CCT295	
5R-2	35	37	697.6	4.73	1.54E−17	0.40	4.31E−09	3.47E−06	2.53	CCT285	
5R-2	35	37	698.1	4.74	1.00E−17	0.43	7.49E−09	1.32E−06	2.44	CCT276	•
7R-1	96.5	98.5	714.0	4.86	4.76E−18	0.40	7.44E−09	6.34E−07	2.40	CCT275	•
7R-1	96.5	98.5	714.0	4.86	2.33E−17	0.41	5.01E−09	4.55E−06	2.47	CCT280	•
11R-CC	10	12	780.6	5.39	2.17E−17	0.44	3.32E−09	6.26E−06	2.50	CCT294	
11R-CC	10	12	780.6	5.39	–	0.43	4.57E−09	–	2.48	CCT296	
14R-1	28	30	810.3	5.64	2.73E−17	0.41	3.53E−09	7.45E−06	2.55	CCT284	
15R-1	62	64	817.1	5.69	3.12E−18	0.42	7.22E−09	4.27E−07	2.54	CCT293	
17R-1	58	63	822.1	5.74	6.95E−21	–	–	–	3.13	CCT297	
17R-1	58	63	822.1	5.74	8.10E−21	0.24	1.86E−08	4.40E−10	3.11	CCT299	
19R-1	23	25	826.7	5.78	8.65E−18	0.41	2.36E−09	3.45E−06	2.47	CCT283	
19R-1	23	25	826.7	5.78	4.51E−18	0.30	2.36E−09	1.83E−06	2.54	CCT298	