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Rupture preparation process controlled by surface roughness on meter-scale laboratory fault

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ABSTRACT

We investigate the effect of fault surface roughness on rupture preparation characteristics using meter-scale metagabbro specimens. We repeatedly conducted the experiments with the same pair of rock specimens to make the fault surface rough. We obtained three experimental results under the same experimental conditions (6.7 MPa of normal stress and 0.01 mm/s of loading rate) but at different roughness conditions (smooth, moderately roughened, and heavily roughened). During each experiment, we observed many stick-slip events preceded by precursory slow slip. We investigated when and where slow slip initiated by using the strain gauge data processed by the Kalman filter algorithm. The observed rupture preparation processes on the smooth fault (i.e. the first experiment among the three) showed high repeatability of the spatiotemporal distributions of slow slip initiation. Local stress measurements revealed that slow slip initiated around the region where the ratio of shear to normal stress (τ/σ) was the highest as expected from finite element method (FEM) modeling. However, the exact location of slow slip initiation was where τ/σ became locally minimum, probably due to the frictional heterogeneity. In the experiment on the moderately roughened fault, some irregular events were observed, though the basic characteristics of other regular events were similar to those on the smooth fault. Local stress data revealed that the spatiotemporal characteristics of slow slip initiation and the resulting τ/σ drop for irregular events were different from those for regular ones even under similar stress conditions. On the heavily roughened fault, the location of slow slip initiation was not consistent with τ/σ anymore because of the highly heterogeneous static friction on the fault, which also decreased the repeatability of spatiotemporal distributions of slow slip initiation. These results suggest that fault surface roughness strongly controls the rupture preparation process, and generally increases its complexity with the degree of roughness.

1. Introduction

It is well known that unstable shear rupture on a frictional interface is often preceded by quasi-static slow slip, which is called rupture nucleation. Because this quasi-static process is expected for the initiation of natural earthquakes, a number of theoretical studies (Dieterich, 1992; Campillo and Ionescu, 1997; Uenishi and Rice, 2003; Rubin and Ampuero, 2005; Ampuero and Rubin, 2008; Kaneko and Lapusta, 2008; Fang et al., 2010; Noda et al., 2013; Tal et al., 2018) and laboratory experiments (Dieterich, 1978a; Okubo and Dieterich, 1984; Ohnaka and Kuwahara, 1990; Ohnaka and Shen, 1999; Nielsen et al., 2010; McLaskey and Kilgore, 2013; Latour et al., 2013; McLaskey and Lockner, 2014; Harbord et al., 2017) have been conducted to construct comprehensive models for earthquake nucleation and to fully understand the process.

Detailed image from the slow slip initiation to the unstable fast rupture was first demonstrated by laboratory experiments (Ohnaka and Shen, 1999; Ohnaka, 2000). It is proposed that the process is composed of three phases: (I) stable, quasi-static phase, (II) unstable, accelerating phase, and (III) unstable fast rupture. Numerical simulations based on the slip weakening friction law (e.g. Shibazaki and Matsu'ura, 1995) or the rate- and state-dependent friction law (e.g. Dieterich, 1992; Rice, 1993) successfully reproduced the overall behavior of the nucleation process on the fault. Recent numerical simulations have been conducted to more closely reproduce the nucleation process observed in laboratory and to improve the understanding of the underlying mechanism (Kaneko and Ampuero, 2011; Kaneko et al., 2016). Even in natural observations, seismic activities supposed to be associated with the

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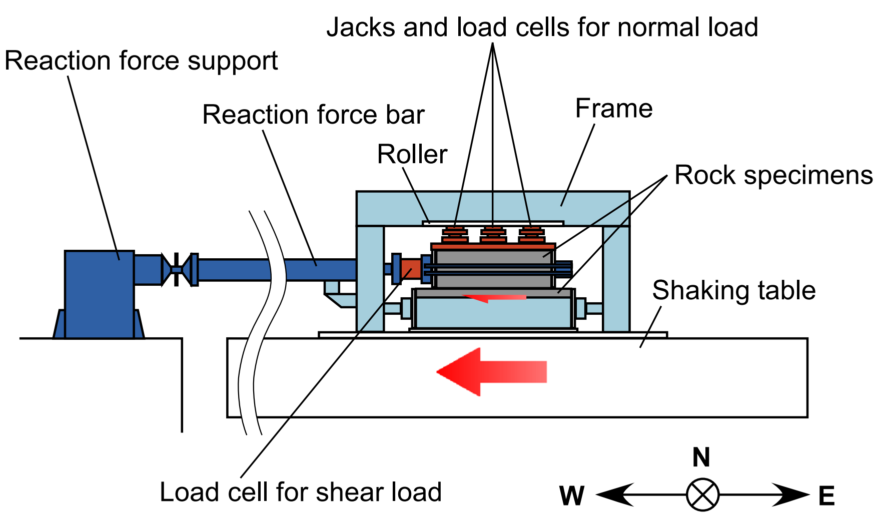

Fig. 1. Schematic diagram of apparatus for experiments in the present study. Orientations are denoted at the right bottom of the Figure. The lower rock specimen was fixed on the shaking table with the frame and moved with the shaking table westward. The upper specimen was stacked on the lower specimen. Its western end was supported by the reaction force bar, which was fixed on the outside floor of the shaking table. The normal load was applied with three hydraulic jacks and the values were measured with three load cells serially connected with them. The shear load was measured with the load cell attached at the eastern end of the reaction force bar.

nucleation process were reported (Ellsworth and Beroza, 1995; Iio, 1995; Beroza and Ellsworth, 1996; Bouchon et al., 2011). Similar seismic activity during the nucleation process was also observed on laboratory fault (McLaskey and Kilgore, 2013).

However, slip behaviors on natural faults are not fully consistent with the nucleation model based on the theoretical studies and laboratory experiments. Kato et al. (2012) found migration of small earthquakes preceding the M_w7.3 foreshock of the 2011 Tohoku-Oki earthquake toward the rupture initiation point of the M_w9.0 mainshock. They suggested that the migration of seismicity was induced by precursory slow slip on the fault, but they also found that the slip did not show power-law type acceleration predicted by the nucleation model. Geodetic observation and data analysis further revealed that a very long-term slow slip lasted for nine years before the 2011 Tohoku-Oki earthquake near the Japan Trench (Yokota and Koketsu, 2015). Bouchon et al. (2013) found long precursory phase associated with increasing number of foreshocks before many interplate earthquakes. They suggested that those foreshocks were triggered by slow slip on the fault. Although Kato et al. (2016) found accelerated seismicity and amount of aseismic slip inferred from repeating earthquakes preceding the 2014 Iquique, Chile, earthquake, the evolution of slip is more episodic and irregular relative to the process often observed in the laboratory. These inconsistencies between natural observations and laboratory experiments can be derived from heterogeneities on the fault associated with rough surface and complicated stress conditions. These heterogeneities might not have been fully simulated in the laboratory, although some experimental studies were conducted on an artificially grinded rough fault (Okubo and Dieterich, 1984; Ohnaka and Kuwahara, 1990; Harbord et al., 2017). Probably, some of the slow slips observed in nature like above cannot be categorized into the conventional nucleation process. In order to deeply understand the actual slip behaviors on natural faults, therefore, it is of great importance to study how rupture initiates under heterogeneous conditions.

In this paper, we investigate the effect of fault surface roughness as one type of heterogeneities on rupture initiation characteristics. Hereafter we call the process from the precursory slow slip initiation to the onset of fast main rupture “rupture preparation process”, which can involve the conventional nucleation process. It is expected that the rupture preparation process can become complicated with the progress of fault surface roughening. In contrast to previous experiments, we repeatedly conducted experiments using the same pair of meter-scale rock specimens to make the fault surface rough naturally as much as possible. As a result, we obtained experimental results with three differently roughened fault surfaces (smooth, moderately roughened, and heavily roughened) under the same loading condition. After describing the experimental procedure, we show the basic characteristics of the observed rupture preparation process on each roughened fault. We further discuss the differences in preparation process among the different surface roughness conditions. Especially, we focus on where the precursory slow slip initiated on each fault, because recent numerical simulation suggested that the location of rupture initiation can greatly affect the resulting coseismic slip distribution and the strong ground motions (e.g. Hok et al., 2011). We then investigate the mechanisms that control the slow slip behavior based on the local stress data obtained with a triaxial strain gauge array. Here, it should be noted that we did not directly measure any roughness parameters (e.g. power spectral density of height, mean height deviation R_a, etc.) of the fault surface in this study. Instead, we estimated the degree of normal stress heterogeneity that is closely related to the surface roughness. This will be discussed in Section 3.1.

2. Experiments

In order to investigate rupture preparation process on a laboratory rock fault in detail, the fault dimension needs to be large enough. A large-scale biaxial friction apparatus, which we used (e.g. Fukuyama et al., 2014), enables us to use meter-scale rock specimens. Fig. 1 shows the schematic diagram. The main feature of this apparatus is that a large-scale shaking table is used as a driving force to shear the rock fault. We used a pair of metagabbro blocks from India as experimental specimens in the present study. Their physical properties are tabulated in Table 1. The lower specimen, which was 2 m long and 0.1 m wide, was fixed on the shaking table with a frame of the apparatus. The upper specimen, which was 1.5 m long and 0.5 m wide, was stacked on the lower one. Thus the nominal contacting area was 1.5 m long and 0.1 m

Table 1
Properties of rock specimen.

Item	Property
Rock type	Metagabbro
Dimension for upper specimen	L1500 mm × W500 mm × H500 mm
Dimension for lower specimen	L2000 mm × W100 mm × H500 mm
Nominal dimension of contacting area	L1500 mm × W100 mm
Initial undulation of contacting surface	< 10 μm
Young's modulus	103 GPa
Poisson's ratio	0.31
P-wave velocity[a]	6919 m/s
S-wave velocity[a]	3631 m/s

[a] Seismic wave velocities were estimated from Young's modulus, Poisson's ratio, and density.