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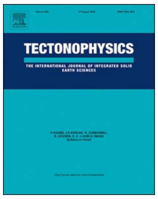

Strain rate effect on fault slip and rupture evolution: Insight from meter-scale rock friction experiments

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ABSTRACT

We conduct meter-scale rock friction experiments to study strain rate effect on fault slip and rupture evolution. Two rock samples made of Indian metagabbro, with a nominal contact dimension of 1.5 m long and 0.1 m wide, are juxtaposed and loaded in a direct shear configuration to simulate the fault motion. A series of experimental tests, under constant loading rates ranging from 0.01 mm/s to 1 mm/s and under a fixed normal stress of 6.7 MPa, are performed to simulate conditions with changing strain rates. Load cells and displacement transducers are utilized to examine the macroscopic fault behavior, while high-density arrays of strain gauges close to the fault are used to investigate the local fault behavior. The observations show that the macroscopic peak strength, strength drop, and the rate of strength drop can increase with increasing loading rate. At the local scale, the observations reveal that slow loading rates favor generation of characteristic ruptures that always nucleate in the form of slow slip at about the same location. In contrast, fast loading rates can promote very abrupt rupture nucleation and along-strike scatter of hypocenter locations. At a given propagation distance, rupture speed tends to increase with increasing loading rate. We propose that a strain-rate-dependent fault fragmentation process can enhance the efficiency of fault healing during the stick period, which together with healing time controls the recovery of fault strength. In addition, a strain-rate-dependent weakening mechanism can be activated during the slip period, which together with strain energy selects the modes of fault slip and rupture propagation. The results help to understand the spectrum of fault slip and rock deformation modes in nature, and emphasize the role of heterogeneity in tuning fault behavior under different strain rates.

1. Introduction

Multiple lines of evidence indicate that the same fault section or rock portion can host a diverse spectrum of slip or deformation modes. In the context of geophysical observations, they include the coexistence of both slow and fast ruptures in the Parkfield section of the San Andreas fault (Veedu and Barbot, 2016) and in the Japan Trench (Ito et al., 2013), and the transient seismicity deepening below the normal brittle-to-ductile transition depth right after a major earthquake (Rolandone et al., 2004; Ben-Zion and Lyakhovsky, 2006; Jiang and Lapusta, 2016). In the context of geological observations, they include the coexistence of pseudotachylytes and mylonites near the base of the seismogenic zone (Sibson, 1980; Lin et al., 2005; Kirkpatrick and Rowe, 2013), and the occasional observation of rock fragmentation in the lower crust (Austrheim et al., 2017). Various ideas have been proposed to explain the diversity and switch of fault slip and rock deformation modes. One view closely follows previous work based on a simple spring-slider model (Marone, 1998a; Scholz, 1998; Baumberger and Caroli, 2006), which states that the slip mode of the slider (mimicking that of a fault portion) in response to an external loading is largely controlled by a competition between a loading system stiffness and a rheological critical stiffness of the fault (Leeman et al., 2016). While this view is quite generic, it is difficult to directly evaluate the stiffness in nature. Alternatively, other studies focus on factors that can be more easily constrained, including slip rate (Noda and Lapusta, 2013), asperity size (Veedu and Barbot, 2016), and strain rate (McLaskey and Yamashita, 2017). Among these factors, the strain rate is of particular interest for geoscience studies, because it is applicable to both localized and distributed deformation and thus may provide a unifying interpretation for understanding both fault slip and rock deformation.

Focusing on the fault slip behavior, there exists a strong inconsistency among different studies on whether increased strain rate tends

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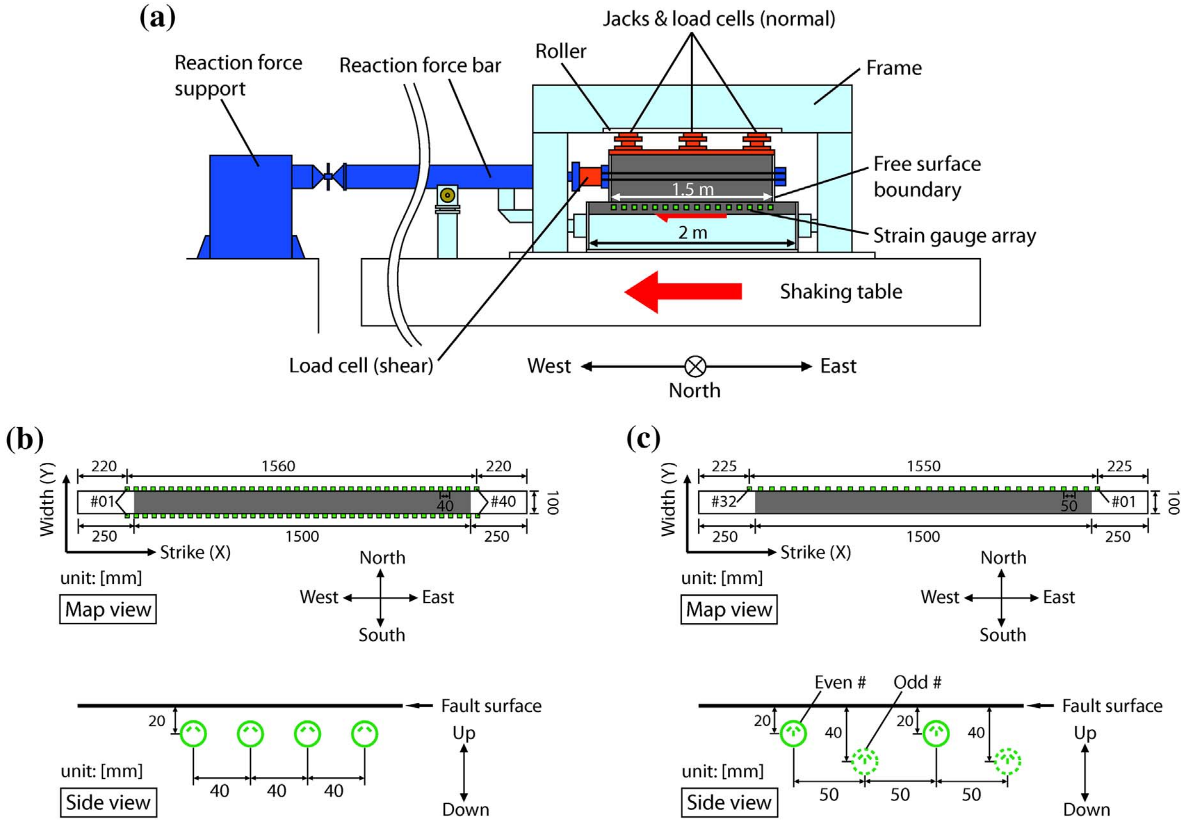

Fig. 1. (a) Schematic diagram of the experimental settings. Normal load is applied from the top of the upper sample, and is measured by three load cells. Shear load is applied by the shaking table movement along the east-west direction beneath the lower sample, and is measured by a load cell located on the western edge of the upper sample. Configurations of strain gauges used for experiments in (b) the LB09 series and (c) the LB12 series. For (b), two-component strain gauges glued on both the northern and southern sides of the lower sample are used for recording the local shear strain/stress. For (c), three-component strain gauges glued on the northern side of the lower sample are used for recording the local shear and normal strains/stresses. The shaded area in (b) and (c) denotes the nominal contact area between the upper and lower samples. Note the very first strain gauges to the western and eastern directions are located outside the contact area. More detailed description can be found in the main text.

to promote or suppress unstable slip. In the context of laboratory experiments, some studies report a transition from stick-slip to stable sliding by increasing the strain rate (or the loading rate for a fixed sample size) (e.g. Ohnaka, 1973; Teufel and Logan, 1978; Wong and Zhao, 1990; Baumberger et al., 1994; Karner and Marone, 2000), whereas other studies observe an opposite trend towards increasingly unstable slip with an increase in strain rate (Kato et al., 1992; Togo et al., 2015; McLaskey and Yamashita, 2017). This raises a need to resolve the strain-rate discrepancy among different experimental studies. A similar discrepancy also exists in natural observations. A positive correlation between the magnitude and the recurrence interval of repeating earthquakes is sometimes observed (e.g. Vidale et al., 1994; Nadeau and McEvilly, 1999; Taira et al., 2009), whereas in other situations a negative correlation can be found (Peng et al., 2005; Chen et al., 2010; Uchida et al., 2015). Since the recurrence interval is generally thought to inversely scale with the loading rate (and thus the strain rate for a fixed fault patch) (Beeler et al., 2001), the variability in the behavior of repeating earthquakes also raises a need to clarify the role of strain rate in controlling the strength recovery and drop of faults.

Some studies have attempted to probe the detailed mechanisms involved behind the strain rate (or loading rate) effect. By equalizing the healing time for different experimental tests, Kato et al. (1992) noted that increasing strain rate could reduce the nucleation zone size of a local rupture event and thus make the fault sliding more unstable. They further suggested that the relative importance of a coupled healing-time effect might help to explain the inconsistent strain-rate dependence of slip mode transition reported by different experimental studies. In a later experimental study, McLaskey and Yamashita (2017) found that rapid increase in loading rate or long healing time could give rise to more unstable rupture along a selected fault portion, by shrinking the characteristic length and time scales required for nucleation. By adopting a one-degree-of-freedom spring-slider model governed by a rate- and state-dependent friction law, Urata et al. (2017) inferred the apparent macroscopic source parameters using the data reported by Togo et al. (2015). They found that the indirect parameter b increases while the characteristic slip distance L_c decreases with increasing the loading rate. In a numerical study of repeating earthquakes with a velocity-weakening patch inside a velocity-strengthening zone, Chen et al. (2010) found that whether the magnitudes of repeating earthquakes positively or negatively scale with their recurrence intervals depends on the size of the weakening patch relative to a critical value. In a similar numerical study of repeating earthquakes, Yoshida et al. (2015) found that the average stress level operating over the velocity-weakening patch could be enhanced by rapidly increasing the loading rate, while the degree of stress enhancement could gradually decay as the fast loading rate continues over multiple cycles. In a study of along-depth seismicity change triggered by the 1992 Landers earthquake, Rolandone et al. (2004) suggested that the transient seismicity deepening could be caused by a strain-rate-controlled increase of stress reaching the brittle strength in the transition zone. Despite these efforts, little has been done so far to generalize the knowledge obtained from a specific model, or to connect the observations and interpretations made at different scales. This limits the understanding of the strain rate effect, because some models are empirical rather than physics-based and because the strain rate effect may manifest itself in different forms at different scales.

To better understand the strain rate effect, we conduct meter-scale rock friction experiments loaded at different rates and make