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Panoramic View of Fault failure Modes from Laboratory and Numerical Experiments

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Certain phenomena in nature occur in Goldilocks zones that provide just the right conditions. One such phenomenon in earthquake science seems to be the occurrence of slow slip preceding dynamic slip. For example, the slow slip before the 2011 Mw 9.0 Tohoku-Oki, Japan (Ito et al., 2013; Kato et al., 2012), 2014 Mw 8.2 Iquique, Chile (Meng et al., 2015; Ruiz et al., 2014) and 2015 Mw 8.4 Illapel, Chile (Huang and Meng, 2018) add to the growing number of such observations. Despite these accumulating evidences, a comprehensive understanding of such observations is lacking. Our quest is to understand the physics behind such phenomena by integrating laboratory and numerical simulations.

One way to find the reasons for the slow-fast phenomena is to test the fault in a controlled setting. Several studies report the occurrence of transient deformation in rock frictional studies (Gu and Wong, 1994; Leeman et al., 2015, 2016; McLaskey and Yamashita, 2017). However, a thorough understanding of the possible parameters that can influence the slow transients is yet to be known. The primary goal of this work is to investigate the effect of material properties on the slow-fast transitional boundary. Here, we report the results of alternating slow and fast events at 23 MPa from the Brittle Rock DeformAtion Versatile Apparatus (BRAVA) at the National Institute of Geophysics and Volcanology (INGV). We show that a mixed slow-fast rupture sequences occur under a set of physical conditions in between those that produce distinct slow-slip events and fast earthquakes (Leeman et al., 2015, Leeman et al., 2016, Scuderi et al., 2016). The laboratory results of the slow-fast behavior at 33 MPa from the Biax machine at the Penn State University confirms that the same material can exhibit the dual mode deformation at a constant normal load.

To depict a broad view of possible failure modes, we integrate the results from the double direct shear biaxial experiments with the dynamic fault modeling (Lapusta and Liu, 2009). The main goal of modeling is to understand the parameters that control the interval between the consecutive slow and fast events. Specifically, the ratio between time since previous event and time to next event, namely the recurrence ratio. We conducted a systematic parameter space study on the dependence of the recurrence ratio on the normal stress, characteristic slip distance, Poisson ratio, asperity size, asperity shape, ratio of friction parameters (a/b) and loading rate. Out of these seven parameters, we found that the loading rate controls the recurrence ratio. It is important to note that the bifurcation from slow-slip to period-two slow and fast ruptures in numerical simulations are only in those models that adequately capture the fault dynamics in three dimensions. Most importantly, the recurrence ratio of the laboratory events and the numerically simulated events are comparable. Overall, our findings highlight a range of possible slip behaviors emerging from the fundamental nature of the fault and provide clues into a potential long preparatory phase that precedes earthquake nucleation.