Strain rate effect on rupture nucleation and mainshock propagation speed

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Multiple lines of evidence have indicated that the same fault portion can host a diverse spectrum of deformation modes. They include the coexistence of pseudotachylite and mylonite near the base of the seismogenic zone, the coexistence of slow slip and unstable rupture in the Japan Trench as well as in the laboratory, and the transient deepening of seismicity below the normal brittle-to-ductile transition depth after a major earthquake. In addition to pressure-temperature condition and material composition, strain rate has been invoked to explain the diversity and switch of deformation modes of solids. In this work, we investigate how strain rate may affect the behavior of fault slip, based on direct shear experiments using meter-scale rock samples made of Indian metagabbro (nominal fault area is 1.5 m x 0.1 m). In addition to the macroscopic frictional behavior measured by load cells, we monitor the local fault behavior utilizing a high-density array of strain gauges mounted close to the synthetic fault (20-40 mm off the fault). We conduct experiments under a constant normal stress of 6.7 MPa, and a constant loading rate ranging from 0.01 mm/s to 1 mm/s. For the highest loading rate, we focus on the early part right after the initial running-in stage, during which fault surface condition has not been significantly altered. We approximately evaluate the strain rate by referring to the applied loading rate over a fixed sample size, while also point out that the actual local strain rate can greatly fluctuate depending on the ongoing deformation mode. Our macroscopic observation shows that for all the tested cases the fault motion is characterized by stick-slip, implying an overall brittle faulting regime. Detailed local observation reveals that quasi-stable slow slip phase preceding unstable mainshocks is a common feature for cases under a low loading rate (e.g. 0.01 mm/s), but can be skipped (below the 50-mm resolution of our strain gauge array) under a high loading rate (e.g. 1 mm/s). Another related local observation is that mainshock propagation speed is often faster under a higher loading rate, possibly exceeding the shear wave speed of metagabbro (i.e. supershear rupture). Based on the well-known theoretical result that the balance between elastic strain energy and fracture energy controls the critical transition length scales and rupture speed (Madariaga and Olsen, 2000), we suggest the following ideas for understanding our laboratory observations. (1) High-rate loading can more efficiently transfer energy to the rock bulk, and the average stress level operating over the entire fault can well exceed that set by the weakest fault patch. (2) High-rate loading can enhance the brittleness of fault rocks by reducing the apparent fracture energy (Freund, 1990): some inelastic process will not have enough time to dissipate energy before the failure criterion is reached near a rapidly stressed rupture front. It should be noted that the above point (2) is not always true, as in other circumstances high-rate loading can cause an increase in the apparent fracture energy through mechanisms such as rupture bifurcation, intense microcracking, and gouge generation. When these scenarios occur, rupture propagation may strongly fluctuate or even get arrested. Therefore, more investigations are needed to categorize strain rate effect during different stages of fault slip.

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