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Laboratory earthquakes across the brittle-plastic transition

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The transition from brittle to plastic deformation corresponds to the regime where brittle fracturing and plastic flow coexist. This transition is fundamental to understand how natural faults behave at varying crustal depth and why large earthquakes generally nucleate at the bottom of the seismogenic zone, at PT conditions where deformation is not fully brittle anymore.

Frictional sliding experiments were performed on Carrara marble saw-cut faults, at confining pressures ranging between 45 and 235MPa, i.e. across the brittle-ductile transition of this well studied lithology (Fredrich et al., 1989). Two different axial loading rates (1.3 μm/s and 0.02 μm/s) and initial surface roughness were investigated. A carbon layer was deposited on the top surface to image heat heterogeneities at the micro-scale (Aubry et al. 2018). White light interferometry was used to measure fault surface topography, before and after the experiments. Depending on the range of pressures and strain rates tested and the roughness of the fault interface, different slip modes and deformation processes were observed.

For all the experiments on smooth faults, static fault friction coefficients ranged between $\sim$0.2-0.45. Regardless of confining pressure, lower loading rates promoted stick-slips. At high loading rates, we observed a transition from quasi-stable sliding (a unique slip event followed by stable sliding) resulting in mirror-like surfaces at low confining pressures (from 45 to 135 MPa) to a stick-slip regime resulting in matte surfaces at high confining pressure (from 180 MPa). Above 90 MPa, laboratory earthquakes (dynamic stick-slips) were observed in a regime where most of the axial strain (up to 70% at the highest confining pressure) was accommodated by bulk plastic deformation of the rock specimen while the fault interface remained locked. Temperature mapping showed that the temperatures reached 1100°C and sometimes over 1500°C along these fault interfaces. Evidence of melting and decarbonation were observed using high-resolution electron microscopy while EBSD revealed that intra-crystalline plastic deformation occurred near the fault interface.

The static friction was always higher for all initially rough interfaces, ranging between $\sim$0.3-0.6. On these rough interfaces, only stable sliding was observed at high loading rates. At 45 and 90 MPa, we observed slow slips and stick-slips, while at 180 MPa, only creep was observed. Along these rough interfaces the amount of gouge produced on the interface was substantial, especially at low pressures.

We conclude that: (i) laboratory earthquakes may nucleate on inherited fault interfaces at brittle-plastic transition conditions; (ii) in this regime where plastic deformation of the bulk and dynamic fault slip may coexist, laboratory earthquakes are promoted when the interface is smooth, or when the loading rate is slow; (iii) stable sliding tends to produce mirror-like surfaces, while stick-slips are associated with matte surfaces, on which the size of the asperities grows with increasing confining pressure, (iv) in a rather counterintuitive manner, when compared to purely brittle rheologies, slower loading rates and higher confining pressures promote the occurrence of laboratory earthquakes associated with increasing plastic deformation, while increasing initial roughness promotes stable sliding.