Geophysical Research Abstracts
Vol. 21, EGU2019-5781, 2019
EGU General Assembly 2019

Fault zone heterogeneity, viscosity contrasts, and fault slip behaviour

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Geophysical observations illustrate that a range of fault slip styles accommodate displacement, ranging from steady creep at plate boundary displacement rates through to episodic earthquake slip at speeds of $\sim$ 1 m/s. Slow slip events (SSEs) represent an intermediate fault slip rate that is faster than plate rate, but too slow to generate observable seismic waves. SSEs are typically observed in or near the transition zone between interseismically locked and fully creeping fault segments. Because SSEs have been observed both up- and downdip of interseismically locked zones, they occur at temperatures ranging from $\leq$ 100˚C to > 500˚C, and are therefore not controlled by a single, thermally activated mechanism. The physical mechanism behind SSEs, however, remains unclear.

Geological observations show that faults can accommodate slip by modes ranging from slip localised on one or more discrete failure planes through to shearing flow distributed within a tabular zone of finite thickness, indicating a large range of possible strain rates in natural faults. Crosscutting relations between brittle and ductile structures demonstrate that strain rate can change both progressively and cyclically within a single fault zone. Cyclic strain rate variations can arise from fluctuations in effective stress, but here we discuss how strain rate transients may also occur in response to internal deformation within a polyphase shear zone.

Both geological observations and numerical models have now shown that a range of slip styles may arise from rheological heterogeneity in space. Such heterogeneity is almost ubiquitous in natural faults, where it may be represented by different minerals in a fault gouge, by anastomosing phyllosilicate networks around competent clasts in melanges, and variably metamorphosed and dehydrated rocks within subducting basalts, to name a few examples. In such examples, spatial variations in strain rate are inevitable, and temporal variations may follow.

If fault slip style is related to fault zone heterogeneity, then there must be certain conditions that are required to produce SSEs, that can be achieved at a large range of temperatures, but yet are not achieved in fault segments that are fully creeping or locked. To explore these conditions, we use the finite element numerical code ‘Underworld’ to analyse the behaviour of two-phase shear zones. We suggest there is a minimum viscosity ratio, above which two things happen: 1) stresses are amplified in the stronger component, potentially leading to failure in strong lenses within a flowing, weaker matrix; and 2) strong lenses interact, and episodically form ‘force chains’ that lead to jamming of the shear zone. The required viscosity contrast (strong/weak) depends on the volume fraction of the weak phase but is typically on the order of 100 – 1000; we suggest that among much evidence for heterogeneity, it is where this level of contrast occurs that slow slip is most likely to arise.