Geophysical Research Abstracts
Vol. 13, EGU2011-12122-1, 2011
EGU General Assembly 2011

Strain localization within a fluid saturated fault gouge layer during seismic shear

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Field observations indicate that seismic shear on a fault is extremely localized, with most strain occurring in a narrow zone less than a few mm wide within a broader ultracataclastic zone (Chester and Chester, Tectonophys.1998; Chester and Goldsby, SCEC 2003; Chester et al., EOS 2003; Heermance et al., BSSA 2003; Wibberley and Shimamoto, JSG 2003; Chester et al., Columbia Un. 2004). Heermance et al. noted that the zone of most intense shear is only 50 to 300 microns wide for the Chelungpu Fault of the 1999 Chi-Chi Taiwan earthquake, as intersected at 350 m depth in a borehole. Also, study (Rice, JGR 2006) of the Chester and Goldsby thin-section micrograph for the surface-exposed Punchbowl fault suggest most shear occurs only over 100 to 300 microns width within a nominal 1 mm wide shear zone. Observations from high velocity friction experiments (Brantut et al., JGR 2008; Kitajima et al., JGR 2010) also show the existence of regions of highly localized slip.

To investigate factors which might set the scale of this localization process, we model a homogeneous, fluid-saturated gouge layer of width h that is being sheared between two saturated poroelastic half-spaces. If the gouge is non-dilatant and has a friction coefficient which is constant, or rate-weakening, then only two forms of deformation are possible (Rice, 2006): homogeneous shear, or slip on a mathematical plane. By assuming a rate-strengthening friction (appropriate for a fault gouge which has achieved high temperatures by ongoing frictional heating), with logarithmic dependence of friction on strain rate, and otherwise following the thermal pressurization formulation by Lachenbruch (JGR 1980) and Mase and Smith (JGR 1987), we find localization of strain to a finite width band to occur within the gouge layer, provided h is large enough.

Neglecting dilatancy we infer the width of this band based on the physical properties of the gouge. For a given shear velocity V accommodated across the gouge layer, the width is shown to be only weakly dependent on h and, within the uncertainty of parameter choices, is predicted to be on the scale of 50 to 100 microns when V = 1 m/s. We also studied the weakening of the gouge layer as a function of time, comparing localized and homogeneous shear, the latter with a constant friction coefficient. We find that the localization process leads to additional weakening of the gouge layer, and examine how this additional weakening is controlled by the properties of the gouge.

Incorporating dilatancy into the model we find this acts as a stabilizing mechanism, with localization being less severe and taking longer to develop. Since our model indicates that dilatancy is more important at lower ambient effective stresses we can deduce that slip should become more localized as we go deeper into the crust. This behavior also has implications for dynamic weakening due to thermal pressurization. Layers with stronger dilatant effects take longer, as the dilatant effects act as sink for pore pressure, but weaken to a lower residual strength at large slip. We use this analysis to predict the width of the localized zone we can expect for at different depths in the crust and comment on the implications this has for dynamic weakening due to thermal pressurization.