

The strength of phyllosilicate-rich fault zones

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The integrated strength of the lithosphere depends to a large degree on the brittle strength of the upper crust. Laboratory experiments at slow slip rates performed by Byerlee (Byerlee, 1978) have shown that, over a very large range of crustal stress conditions, the strength of faults as described by the coefficient of friction, only varies between 0.6 and 0.85, regardless of the material used in the experiments. This observed behaviour is termed Byerlee's rule. There are several lines of evidence that suggest that the strength of the brittle crust is dictated by Byerlee's rule. First, the angle between any fault plane and the principal tectonic driving stress component should be 25 to 30° if Byerlee's rule applies. Compilations of >M5.5 earthquakes has shown angles in that range, albeit with quite a lot of scatter (Collettini & Sibson, 2001; Sibson & Xie, 1998). Importantly, no earthquakes were recorded that show an angle greater than the predicted frictional lock-up angle (where it should be more favourable to create a new fault than to reactivate slip on the severely mis-oriented fault). Second, crustal stress measurements made in various boreholes show a variation in differential stress with depth that is entirely consistent with slip on faults with friction coefficients commensurate with those predicted by Byerlee (Townend & Zoback, 2000). Consequently, the inference has been made that crust strength is controlled by faults obeying Byerlee's rule.

One notable exception to Byerlee's rule is the frictional behaviour of clays and phyllosilicates. They have consistently been shown to possess friction coefficients that are much less than the 0.6 to 0.85 Byerlee range. Large tectonic faults commonly contain phyllosilicate-rich fault cores and the applicability of Byerlee's rule to these faults is open to question (Chester et al.,

1993; Faulkner et al., 2003; Wibberley & Shimamoto, 2003). The strength of the San Andreas fault in California has been a subject of debate for the past 40 years. Stress measurements surrounding the fault show the greatest principal stress makes a high angle (75 - 80°) to the fault, suggesting the fault is a severely mis-orientated fault (Hickman & Zoback, 2004). Likewise, field and seismological evidence for the existence of low-angle normal faults, also severely mis-oriented with respect to the driving stress, are compelling (Chiaraluca et al., 2007; Smith & Faulkner, 2010).

Laboratory measurements at slow slip rates of the frictional properties of phyllosilicates has indicated that their dry strength may be controlled by the interlayer bond energy (ILBE) between the phyllosilicate layers (Moore & Lockner, 2004). It is suggested that for phyllosilicate minerals with ILBE of 70 kcal/mol or less, dry shear occurs mainly by breaking through interlayer bonds between basal planes. However, this relationship is not always clear (Behnsen & Faulkner, 2012). The low-stress behaviour of phyllosilicates, where ILBE may exceed the stress required to slide intact coherent crystals past each other, shows much higher friction coefficients.

The frictional behaviour of phyllosilicates changes significantly at slip velocities approximating to earthquakes. Several clays tested in the laboratory under slow slip conditions (~5 µm/s) showed velocity strengthening behaviour, indicating that earthquakes are unlikely to nucleate on clay-rich faults. This concurs with observations of a 'seismic gap' between 0 and 10 km depth in accretionary forearcs, where clays are thought to dominate. Under earthquake slip (~1 m/s) velocity, the clay-rich samples show significant slip weakening and, when wet, have a negligible

fracture energy, which indicates that they will pose little resistance to a propagating earthquake rupture. The implication is that earthquakes do not nucleate in clay-rich faults, but may pose little resistance to earthquake ruptures that nucleated elsewhere, in less clay-rich regions of the fault zone.

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