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Deformation processes at seismic slip rates in water-depleted and water-rich smectite-bearing gouges

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Smectite clay minerals are among the most common components of fault cores in shallow sections of subduction zone megathrusts and landslide decollements. Consequently, deformation processes at seismic slip rates (1 m/s) in smectites control the mechanics of megathrust earthquakes and landslide collapse. To investigate the deformation processes, rotary shear experiments on smectite-rich gouge layers (70/30 wt.% Ca-montmorillonite/opal) were performed. The experiments were conducted at ambient temperature and at 5 MPa normal stress. The gouges were sheared under vacuum (10^{-3} mbar), room humidity (i.e., water-depleted) and liquid water (i.e., water-rich) conditions, at slip rates of $0.0003 \leq V \leq 1.5$ m/s and displacements of $0.1 \leq d \leq 30$ m. The temperature evolution with slip was determined using thermocouples and subsequently compared to numerical results obtained through a finite element model. The permeability of the gouge layer was measured using the pore pressure oscillation method prior to the rotary experiments. Before and after the experiments, mineralogic composition and amorphous material content were investigated via quantitative X-ray powder diffraction and microstructural analyses were performed using advanced electron microscopy. The deformation processes were strongly controlled by the water content of the gouge layers. Under water-depleted conditions, grain size reduction producing nanoparticles controlled the evolution of friction coefficient at all slip rates. Coseismic dynamic weakening ($\mu \sim 0.2 - 0.3$) occurred by combined thermal decomposition or melting (with decreasing water content) and pressurization of water released by dehydration of smectite interlayers. Under water-rich conditions, grain size reduction was minor and development of nano-foliations occurred. Within the nano-foliations, the observed dynamic weakening ($\mu \leq 0.15$), which occurred at all slip rates and for short displacements (d < 0.1 m), was due to water lubrication resulting in combination with pore fluid pressurization by shear-enhanced compaction. The subsequent friction coefficient evolution depended on the balance between, (1) the dissipation of pore pressures, (2) the dehydration of interlayer water and (3) the thickening of the nano-foliation layers. At higher displacement and slip rates, sustained dynamic weakening was aided by vaporization of the pore water and resulted in a switch to deformation processes typical of water-depleted conditions. These observations scaled to natural conditions would imply that the presence of liquid water in smectites has a lubricating effect, pressurizes the slipping zone and renders the smectite-rich gouges prone to accommodate large seismic slips. In megathrust environments, such lubricating effect may result in the preferential propagation of seismic ruptures during megathrust earthquakes in smectite- and water-rich sediments at shallow depths. Similarly, the presence of water can promote large displacements during landslide collapse.