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Microstructural analysis of deformed calcite veins of SAFOD core samples with implications for the San Andreas Fault rheology

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The microstructures of four core samples from the San Andreas Fault Observatory at Depth (SAFOD) were investigated with optical and transmission electron microscopy. These samples, consisting of sandstone, siltstone, and cataclastic shale from phase III of the drilling campaign (3141 - 3307 m MD), contain mainly quartz, feldspar, clays, and amorphous material. Microstructures indicate intense shearing and dissolution-precipitation as main deformation processes. The samples also display abundant veins filled with calcite showing uniform cathodoluminescence colors, in particular two samples collected close to the creeping fault segments at depths of 3194 and 330 m. Within the veins calcite grains are deformed with varying intensity indicated by twinning and crystal plasticity. Dislocation densities (ranging from $\approx 3{\cdot}10^{12}$ m^{-2} to $\approx 3{\cdot}10^{13}$ m^{-2}) and twin line densities ($\approx$ 22 mm^{-1} – 165 mm^{-1}) are used as paleo-piezometers. The corresponding estimates of differential stresses vary substantially between 33 and 132 MPa, deduced from dislocation density and 92 – 251 MPa obtained from twin density, possibly reflecting grain scale stress perturbations. Mean values of stress estimates from dislocation densities and twinning are 68 $\pm$ 46 MPa and 168 $\pm$ 60 MPa, respectively. The lower stress bound agrees well with stress estimates from borehole breakout measurements performed in the SAFOD pilot hole. In contrast, the stress estimates from twin density may be an upper bound indicating peak stress conditions, possibly influenced by short term seismic events. Residual lattice strains determined with microfocus Laue diffraction of strongly twinned grains within one sample yield an average stress of 220 MPa, in agreement with results based on the twin density piezometer. From these data and assuming hydrostatic pore pressure, frictional sliding of the San Andreas Fault at the SAFOD site is constrained to friction coefficients between 0.24 and 0.33. These low friction values may be related to the presence of clays, talc, and amorphous phases found in the fault cores and support the hypothesis of a weak San Andreas Fault.