Heterogeneous stresses and deformation mechanisms at shallow crustal conditions, Hungaroa Fault Zone, Hikurangi Subduction Margin, New Zealand

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The Hungaroa Fault Zone (HFZ), an inactive thrust fault along the Hikurangi Subduction Margin, accommodated large displacements (~4–10 km) at the onset of subduction in the early Miocene. Within a 40 m-wide high-strain fault core, calcareous mudstones and marls display evidence for mixed-mode viscous flow and brittle fracture, including: discrete faults; extensional veins containing stretched calcite fibers; shear veins with calcite slickenfibers; calcite foliation-boudinage structures; calcite pressure fringes; dark dissolution seams; stylolites; embayed calcite grains; and an anastomosing phyllosilicate foliation.

Multiple observations indicate a heterogeneous stress state within the fault core. Detailed optical and electron backscatter diffraction-based texture analysis of syntectonic calcite veins and isoclinally folded limestone layers within the fault core reveal that calcite grains have experienced intracrystalline plasticity and interface mobility, and local subgrain development and dynamic recrystallisation. The recrystallized grain size in two calcite veins of 6.0±3.9 µm (n=1339; 1SD; HFZ-H4-5.2m_A;) and 7.2±4.2µm (n=406; 1SD; HFZ-H4-19.9m) indicate high differential stresses (~76–134 MPa). Hydrothermal friction experiments on a foliated, calcareous mudstone yield a friction coefficient of µ≈0.35. Using this friction coefficient in the Mohr-Coulomb failure criterion yields a maximum differential stress of 55 MPa at 4 km depth, assuming a minimum principal stress equal to the vertical stress, an average sediment density of 2350 kg/m^3, and hydrostatic pore fluid pressure. Interestingly, calcareous microfossils within the foliated mudstone matrix are undeformed. Moreover, calcite veins are oriented both parallel to and highly oblique to the foliation, indicating spatial and/or temporal variations in the maximum principle stress azimuth.

To further constrain HFZ deformation conditions, clumped isotope geothermometry was performed on six syntectonic calcite veins, yielding formation temperatures of 79.3±19.9°C (95% confidence interval). These temperatures are well below those at which dynamic recrystallisation of calcite is anticipated and exclude shear heating and the migration of hotter fluids as an explanation for dynamic recrystallisation of calcite at shallow crustal levels (<5 km depth).

Our results indicate that: (1) stresses are spatiotemporally heterogeneous in crustal fault zones containing mixtures of competent and incompetent minerals; (2) heterogeneous deformation mechanisms, including frictional sliding, pressure solution, dynamic recrystallization, and mixed-mode fracturing accommodate slip in shallow crustal fault zones; and (3) brittle fractures play a pivotal role in fault zone deformation by providing fluid pathways that promote fluid-enhanced recovery and dynamic recrystallisation in the deforming calcite at remarkably low temperatures. Together, field geology, microscopy, and clumped isotope geothermometry provide a powerful method for constraining the multiscale slip behavior of large-displacement fault zones.