Internal Structure and Slip Mechanisms of Continental Faults

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Brittle faults in the upper crust often are modeled as simple surfaces bounded by tip and branch lines. In detail, however, faults are tabular zones of fractured and brecciated rock containing narrower zones of concentrated shear and slip surfaces (e.g., Sibson, 1986). For larger faults the fractured zones may be hundreds of meters thick. Although fracturing and brecciation often are associated with random fabrics, field studies have demonstrated that most brittle faults have similarly ordered internal structure. Through detailed study of fault internal structure it is possible to determine the fundamental mechanisms of deformation and recovery, slip processes, and the evolution of structural state (e.g., Chester & Logan, 1986). With such information field studies can help constrain models and test hypotheses for the physical and mechanical properties of brittle faults (e.g., Chester et al., 1993). In this presentation I will use the results of field studies of exhumed, large displacement faults of the San Andreas system to address three important aspects of brittle faults relevant to understanding the mechanical behavior of the brittle crust.

Fault development and Mechanical Properties

Brittle faults grow from fractures or pre-existing flaws through tip propagation, linkage and coalescence to form through-going shear surfaces. These processes produce a breakdown in strength from the relatively high fracture strength of intact rock in the tip regions to the residual frictional strength of fault surfaces. Brittle faulting and frictional behavior are well characterized through laboratory experimentation. In many tectonic settings the strength of faulted crust compares favorably with frictional behavior as determined in the laboratory (Sibson, 1994). However, there is some evidence that some faults, such as the San Andreas fault, are significantly weaker (e.g., Hickman, 1991). If so, then what are the weakening mechanisms and is weakness related to the large magnitude of displacement? Structural changes occur within fault zones as displacement accrues, and there are several weakening processes that may be associated with these changes. Weakening processes include the production of weaker phases through hydration reactions, a switch in deformation mechanism caused by water–rock reactions or particle size reduction, and reducing the roughness of slip surfaces. Additional weakening processes that may be promoted by the development of a mature fault structure include reductions in effective normal stress through elevation of pore fluid pressure and the activation of dynamic weakening mechanisms during seismic slip.

Fluids and Faulting

It is well known that faults can act as both barriers and conduits to the flow of fluids in the crust. On the basis of the internal structure, the permeability characteristics of faults may be predicted in a qualitative sense (e.g., Caine et al., 1996). In some cases laboratory and in situ measurements have been used to determine absolute permeability and to address scaling issues. Because fault permeability depends on fracturing, generation of fine particles by cataclasis, mineral alteration, and cementation, the permeability structure of faults may change over several temporal scales: from times greater than the life of the fault to times less than the recurrence interval for earthquakes. It is documented that fluid flow along faults may be triggered by slip events due to creation of along-fault permeability (Sibson, 1990). In certain environments it appears that the development of elevated fluid pressure by compaction or prograde metamorphism at depth may trigger fault slip and lead to fault-valve behavior. It is an open question as to whether the porosity and permeability structure of a mature fault zone and earthquake cycling favors the generation and maintenance of locally elevated pore-fluid pressures, or whether an external source of fluids is necessary.

Seismic Slip Processes

The fundamental physical processes of friction during seismic slip are poorly understood, but are likely to be different than the processes that dominate at lower rates during earthquake nucleation and interseismic periods. At high velocities, dynamic and thermal effects could contribute significantly to reducing friction. The magnitude of slip necessary to produce dynamic weakening and the magnitude of dynamic friction influence the energy balance of earthquakes and earthquake rupture characteristics. Dynamic weakening could explain the low strength of the San Andreas relative to nearby smaller faults because the weakening processes may be activated only during large earthquakes (and thus on large, mature faults). Dynamic weakening processes due to thermal effects include friction melt lubrication and thermal pressurization of pore fluids. Other weakening processes include dynamic unloading effects by acoustic fluidization, opening modes of slip, and wrinkle-like slip pulse rupture modes. Thermal induced weakening is favored on strong faults, but could be important for any large slip event as long as slip is very localized. Although the operation of the different dynamic weakening processes could be recorded by internal fault structure, this has received little attention in field studies to date (Chester & Chester, 1998).

Reading List

Hickman, S.H., Stress in the lithosphere and the strength of active faults, Reviews of Geophysics, Supplement, 29, 759-775, 1991.
(*A good review of the evidence for low shear stress on the San Andreas fault*)

Sibson, R.H., An assessment of field evidence for "Byerlee" friction, in Faulting, friction, and earthquake mechanics; Part 1., edited by C.J. Marone, and M.L. Blanpied, pp. 645-662, Birkhaeuser Verlag, Basel, Switzerland, 1994.
(*Review of evidence that many faults in the crust follow Byerlee's relation*)

Chester, F. M., and J. M. Logan, Implications for mechanical properties of brittle faults from observations of the Punchbowl fault zone, California, Pure Appl. Geophys., 124, 79-106, 1986.
(*An example of a field-laboratory study to infer deformation mechanisms and relative mechanical properties*)

Chester, F.M., J.P. Evans, and R.L. Biegel, Internal structure and weakening mechanisms of the San Andreas fault, Journal of Geophysical Research, 98, 771-786, 1993.
Chester, F. M., and J. S. Chester, Ultracataclasite structure and friction processes of the San Andreas fault, Tectonophysics, 295, 199-221, 1998.
(*Two field studies to infer mechanisms of slip and test hypotheses for weakening the San Andreas*)

Sibson, R.H., Brecciation processes in fault zones; inferences from earthquake rupturing, Pure Appl. Geophys., 124, 159-175, 1986.
(*An example of using fault structure to infer earthquake processes*)

Caine, J. S., Evans, J. P., and Forster, C. B., Fault zone architecture and permeability structure, Geology, 24, 1025-1028, 1996.
(*Presents simple models for fault permeability based on internal fault structure*)

Sibson, R.H., Conditions for fault-valve behavior, in Deformation Mechanisms, Rheology and Tectonics., edited by R.J. Knipe, and E.H. Rutter, pp. 15-28, Geological Society of London, London, United Kingdom, 1990.
(*Describes conditions favorable for fluid discharge along faults*)