Structure and Petrology of the Kern Canyon Fault, California: A Deeply Exhumed Strike-slip Fault

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Annual Project Summary

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Investigations Undertaken

A long-standing problem in earthquake mechanics is our incomplete understanding of the physical and chemical processes that control earthquake nucleation and rupture propagation along mature faults, such as faults of the San Andreas system, California. To date, numerous hypotheses have been put forward to explain the apparent weakness of the San Andreas fault (e.g., Scholz, 2000; Hickman et al., 1994; Zoback et al., 1987). Similarly, a number of hypotheses have been proposed to explain observations of seismicity on faults, including the depth extent of seismogenesis, occurrence of aseismic creep, and complexity of earthquake rupture, such as heterogeneous moment release, and triggered slip. Critical to many of these hypotheses are specific assumptions about the structure, petrology, and fluid environment of fault zones. Although we have increased our understanding of these parameters significantly through detailed field studies of exhumed faults, there is a general lack of observations of large-displacement, strike-slip faults at depths greater than about 5 km, i.e., from the middle of the seismogenic zone in the continental crust. As such, too few data are available to constrain or test many of the existing hypotheses for fault weakening and earthquake mechanics. This study is the first part of a detailed structural and petrological investigation of the mechanics and mechanisms of seismic faulting in the mid- to lower-portion of the seismogenic regime. The goal is to provide critical information on the physical and chemical processes that operate within this zone over the earthquake cycle through field study of the Kern Canyon fault, CA (Figure 1). Portions of this investigation have been performed in collaboration with L. Neal (TAMU), R. Wintsch (Indiana Univerisity), and F. Chester (TAMU).

The Kern Canyon fault zone is part of a deeply exhumed, large displacement, strike-slip fault system in batholithic, metasedimentary and metavolcanic rocks of the southern Sierra Nevada (Figure 1; e.g., Moore and du Bray, 1978). Geologic mapping documents that the system is approximately 140 km in length and parallels the marginal faults of the Sierra Nevada (Moore, 1981; Moore and Sisson, 1984; Ross, 1986), extending from south of Lake Isabella northward towards Mt. Whitney. The Kern Canyon fault zone (KCFZ) generally is regarded as a narrow, brittle fault zone of Cenozoic age (Moore & du Bray, 1978; Ross, 1986). Along the central and northern portions of the KCFZ there is evidence of an earlier, wider zone of ductile shearing referred to as the proto-Kern Canyon fault zone (PKCFZ) (e.g., Busby-Spera & Saleeby, 1990). The PKCFZ is a regionally extensive, synplutonic dextral shear zone that may be the southern continuation of the axial intrabatholithic break of the Sierra Nevada (Saleeby and Busby-Spera, 1993; Kistler, 1993). The PKCFZ and KCFZ diverge at about Kernville. The KCFZ continues to the southwest through Engineer Point and Lake Isabella dam (Ross, 1986), and the PKCFZ continues southeast to the eastern end of the Tehachapi Mountains (e.g., Busby-Spera & Saleeby, 1990; Saleeby & Busby-Spera, 1993).

At Engineer Point, a prominent peninsula extending northward into Lake Isabella, the fault consists of a broad fractured and mineralogically altered damage zone several hundred meters thick (Figure 2; Ross, 1986). The fault is located along and strikes approximately parallel to the eastern side of the peninsula. Correlation of offset plutonic and metamorphic rocks across the Kern Canyon fault in the vicinity of this peninsula suggests dextral separation of approximately 15 km (Ross, 1986; Moore & du Bray, 1978). Previous reports also suggest that there may have been a significant component of dip-slip in this region (Treasher, 1948; Engel, 1963; Saleeby, 1992). Rock exposures are present over the peninsula and along the wave cut beaches. We visited the fault during mid-summer months when water levels in the reservoir are moderate to high (~2595'), and also during low-water (~2572') common during the fall and spring when a greater portion of the fault zone is exposed and most of the peninsula is dry and accessible.

Work to date has focused on documenting the overall petrology and structure of the fault zone at Engineer Point. Fault rock structures, relative intensity of hydrothermal alteration, and protolith rock type were mapped at a scale of 1:6000. Mesoscopic scale fracture density traverses (Figure 2) and fault and fracture orientations have been measured at the regional and fault zone scales. Approximately 30 oriented samples representative of the various protoliths and fault rocks were collected for optical microscopy and quantitative microprobe analyses.

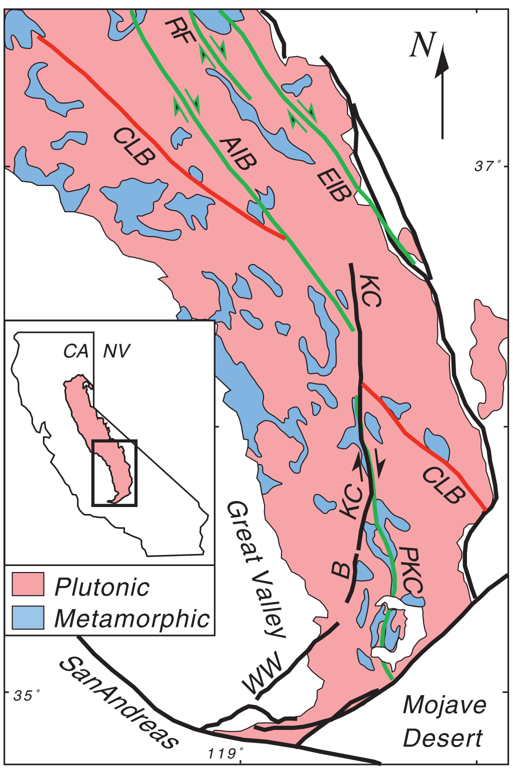

Figure 1. Map of the southern Sierra Nevada batholith showing the location of the Kern Canyon fault zone (KC) relative to other tectonic features, including the axial intrabatholithic break (ABI), cryptic lithospheric boundary (CLB), eastern intrabatholithic break (EBI), proto-Kern Canyon fault (PKC), Rosy Finch shear zone (RF), Breckenridge fault (B), and White Wolf fault (WW) (modified from Saleeby and Busby, 1993, and Kistler, 1993).

Results

Structure: The Kern Canyon fault zone at Engineer Point consists of two distinct shear zones, a phyllonite and a cataclastic zone. Within the cataclastic zone two distinct types of cataclastic fault rocks exist recording two brittle faulting phases. The dominant cataclastic zone trends N20˚E and contains breccias, cataclasites, and foliated cataclasites, and displays mesoscopic, localized slip surfaces. This zone displays mineralogies that are similar to the phyllonite, except that it contains greater volumes of calcite. The internal structure of the cataclastic zone is similar to that of other large displacement faults in that it consists of a broad zone of fractured and altered rock bounding a relatively narrow core of highly sheared fault rocks (e.g., Chester et al., 1993).

The dominant cataclastic zone is cut by faults formed during the second phase of brittle deformation. Distinctly younger shears occur within and are roughly parallel to the cataclastic zone, and are lined with thin layers of hematite-cemented gouge. The hematite-cemented gouge consists of an extremely fine grained matrix containing porphyroclasts of older cataclasites. Clast compositions vary, and most show evidence for alteration and replacement reactions. Slip lineations in the gouge suggest a large component of dip-slip. On the basis of cross-cutting relations and relative development of the different brittle fault rocks, it appears that the gouge represents the latest stage movements and that the magnitude of dip-slip motion is small relative to that accommodated by the prominent right-lateral cataclastic zone. Although locally variable in thickness and deformation intensity, the overall damage zone generally displays an ordered progression of mesoscopic scale structures recording increased deformation towards the fault core.

The phyllonite zone trends N40˚E, and is located west of the cataclastic zone. At the southern end of Engineer Point, the phyllonite is spatially separate from the cataclastic fault and is relatively unaffected by brittle deformation. The phyllonite is cut by the cataclastic fault in the central portion of the peninsula and segments of the phyllonite zone are present within the cataclastic zone further north. The phyllonite zone is on the order of 10 m wide and consists of a narrow layer of phyllonitic material bounded by protophyllonite that grades into altered host-rock. Fault-related mineral alteration reflects the transformation of feldspars to white mica, quartz, calcite, and albite. Quartz fabric and synshearing mineral reactions imply phyllonite formation at brittle-plastic transitional conditions.

Zones of chemical alteration roughly correlate with the damaged zone of the faults, and rocks with greatest degree of alteration occur closest to the fault cores, and to larger subsidiary faults in the surrounding host rock. Smaller alteration halos about fractures and small shears also are displayed in outcrop. Overall, the field relations suggest that the faults were fluid-saturated, the faulting environment was hydrothermal, and that fluid flow and mineralization was episodic and coupled with fault-slip.

Timing Relations. Offset of igneous contacts and acidic dikes across the phyllonite suggest approximately 300 m of right-lateral separation. The phyllonite is cut and dissected by the westernmost observed trace of the cataclastic fault. Fault-bounded slices of exotic rocks, such as tuff and limestone, within the cataclastic fault zone imply kilometers of slip on the slip surfaces.

Quartz and calcite fracture-fill is common in the damaged zone of the cataclastic fault, and veins up to several decimeters thick are present near the fault core. In general, the thickness of veins decreases with distance from the fault core. Individual veins show evidence of more than two fracture and cementation events, and the veins and cataclastic shears are mutually cross-cutting indicating that fracture and cementation occurred during faulting.

Fault and Fracture Fabric. The regional fracture fabric is characterized by two steeply dipping fractures sets striking approximately N05E and N60W. In contrast, the fractures at Engineer Point display a strong preferred orientation characterized by steeply dipping fractures striking N60E, and a weaker set that reflects the regional fracture fabric. Fractures filled with quartz and calcite, clearly associated with synfaulting alteration and deformation, display two broad sets, a fault-parallel set, and a set that is oriented at approximately 45˚ to the Kern Canyon fault and consistent with right-lateral strike-slip. Subsidiary faults are common in the intensely fractured rock of the damage zone near the foliated cataclastite fault core. The subsidiary faults constitute a quasi-conjugate set of steeply dipping strike-slip faults that have a bisector oriented approximately 50˚ to the Kern Canyon fault. Although there is considerable scatter in vein orientation, the average orientation of veins bisects the quasi-conjugate set of subsidiary strike-slip faults. The fracture and subsidiary fault fabrics at Engineer Point indicate that the main phase of cataclastic faulting was right lateral, strike-slip. The phyllonite displays an S-C fabric with right-lateral C' surfaces. The nearly vertical intersection of surfaces and asymmetry indicate right-lateral strike-slip also dominated in the phyllonite zone.

Alteration and Ductile Shearing. A traverse across the phyllonite zone from the undeformed protolith (Wagy Flat granodiorite) on the east to the Alta Sierra granodiorite on the west was used to characterize the syndeformation-alteration reactions important during the ductile phase of faulting. The protolith (Wagy Flat granodiorite) is a coarse-grained granoblasitc rock composed of zoned plagioclase (An_{40-45} cores to An_{25} rims), potassium feldspar, biotite, quartz, sphene and minor amounts of hornblend. At the microscopic scale the quartz grains display a relatively low density of intragranular microfractures, and biotite crystals are slightly undulose. Four domains may be distinguished within the damage zone of the phyllonite on the basis of a progressive increase in deformation and different chemical reaction products. Preliminary quantitative microprobe analyses show that the outermost domain of the damage zone is characterized, in part, by the pseudomorphic replacement reactions of anorthite to albite (An_{02-00})+muscovite+calcite; biotite to vermiculite, and sphene to rutile+quartz. In higher strained, domains vermiculite has altered to chlorite, and albite has altered to mica+quartz. Microscopic phyllonite zones appear along albite-albite grain boundaries and along boundaries between different phases. These zones are composed phengitic mica and display strong lattice preferred orientation and well-developed mica contiguity. The two additional domains display increasing degree of phyllonite development and increasing deformation, healing, sealing and recrystallization of quartz, and consumption of feldspars. In support of previous studies (e.g., Wintsch et al., 1995; Shea and Kronenberg, 1993) we have found that the alteration of anorthite and albite to muscovite alone clearly were not sufficient to localize strain, as there is no evidence that early formed micas from these reactions were reoriented and concentrated by shear to form phyllonite zones. It appears that calcite produced by alteration of primary plagioclase (An_{40}) either left the system, or may have concentrated in veins at shallower depths.

The only deformation associated with the first stage of reactions is fracturing, and most fractures were sealed and healed. Thus, these initial reactions were chemically driven in an open system, probably from the influx of acidic meteoric waters along fracture permeability, provided a source for Ca^{++}, and were independent of phyllonite formation and apparently independent of significant strain. With further strain, it appears that the quartz and mica reaction products are spatially differentiated through diffusive mass transfer to produce the concentrated mica seams and zones of finely recrystallized quartz. The distribution of phases suggests that some reactions require deformation or at least a directed stress.

The present characterization of the structure and petrology of the Kern Canyon fault at Engineer Point will provide the basis for the future detailed structural, petrologic and geochemical analyses to identify the mechanisms of fault slip and the role of chemical reactions in the seismogenic zone. Future work will begin with a characterization of slip localization in the cataclastic zone and investigation of mineral reactions within each structural domain to identify the key element exchange reactions and determine to what extent and at what scale the fault system was open or closed.

Conclusions. At Engineer Point, the Kern Canyon fault displays approximately 15 km of right lateral separation, and consists of a fractured, sheared and mineralogically altered zone several hundred meters thick. At least three distinct phases of deformation are recorded in the zone: an early phase of ductile shear within an S-C phyllonite, a subsequent, dominant phase of brittle faulting characterized by a throughgoing zone of cataclastic rocks, and a late stage of minor faulting along thin, hematitic gouge zones. The phyllonite zone trends N20-40E and displays extensive retrograde alteration primarily involving transformation of feldspar to mica, calcite and quartz. The cataclastic zone cuts the phyllonite, trends N20E, and consists of a relatively narrow core of foliated cataclasites cut by mesoscopic slip surfaces. Mesoscale fracture intensity decreases linearly with log distance from the cataclastic core and approaches background levels at approximately 50 m. S-C fabrics and subsidiary fault slip data indicate that both the phyllonitic and cataclastic shear zones were dominantly strike-slip. Slip lineations on the hematitic gouge zones suggest normal oblique-slip. The damage zone of the fault contains many quartz- and calcite-filled veins and the cataclastic rocks often are calcite-cemented. Some quartz veins are greater than 1 m thick. Fault-parallel and pinnate veins exist along the foliated cataclasites and localized slip surfaces. Cross cutting relations indicate quart-filled veins began forming during the phyllonite phase, and calcite-filled veins formed largely during the cataclastic-

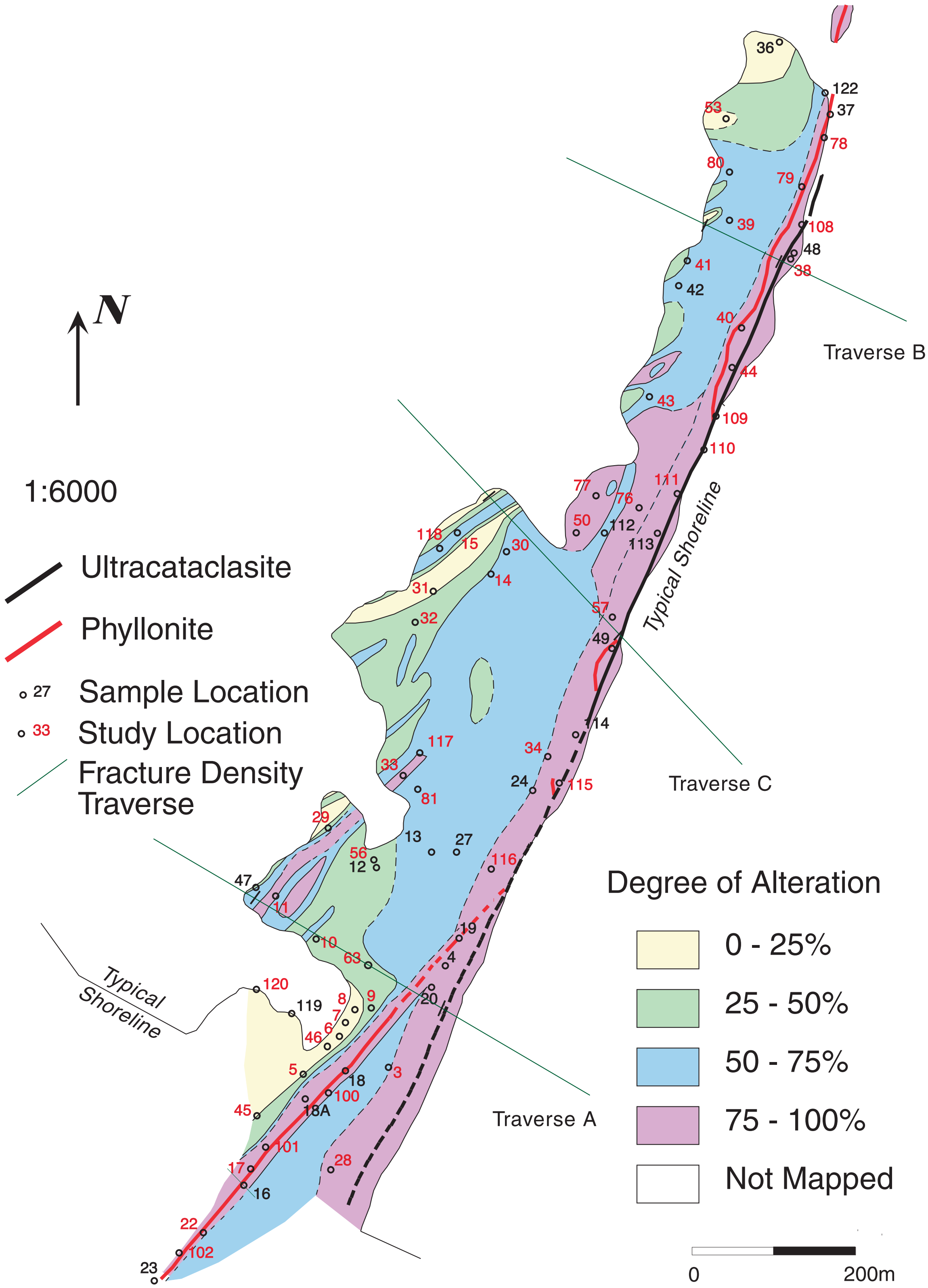

Figure 2. Map of faults and alteration intensity at Engineer Point. Alteration intensity defined by visual estimation of the volume of rock that is noticeably altered at the outcrop scale.

faulting phase. The structures and synfaulting mineral reactions record faulting under evolving fluid chemistry and metamorphic conditions possibly associated with progressive unroofing during faulting. Future work will involve additional structural analysis of the cataclastic zone as well as additional petrologic and geochemical analyses of the fault rocks to determine the distribution of slip, mechanisms of deformation, and chemical reactions during faulting.

References Cited

Busby-Spera, C.J. and Saleeby, J.B., 1990, Intra-arc strike-slip fault exposed at batholithic levels in the southern Sierra Nevada, California, Geology, 18, 255-259.

Chester, F.M., Evans, J.P., and Biegel, R.L., 1993, Internal structure and weakening mechanisms of the San Andreas fault, JGR, 98, 771-786.

Hickman, S., Zoback, M., Younker, L., and Ellsworth, W., 1994, Deep scientific drilling in the San Andreas fault zone: Eos (American Geophysical Union Transactions), v. 75, p. 137-140.

Kistler, R.W., 1993, Mesozoic intrabatholothic faulting, Sierra Nevada, California, in Mesozoic Paleogeography of the Western United States – II, eds., Dunne, G.C. and McDougall, K.A., Pacific Section SEPM, Book 71, 247-262.

Moore, J.G., 1981, Geologic map of the Mount Whitney quadrangle, Inyo and Tulare County, California: U.S. Geological Survey Geologic Quadrangle Map GQ-1545.

Moore, J.G. and du Bray, E., 1978, Mapped offset on the right-lateral Kern Canyon fault, Sierra Nevada, California, Geology, 6, 205-208.

Moore, J.G. and Sisson, T.W., 1985, Geologic map of the Kern Peak quadrangle, Tulare County, California: U.S. Geological Survey Geologic Quadrangle Map GQ-1584.

Ross, D.C., 1986, Basement-rock correlations across the White Wolf-Breckenridge-southern Kern Canyon fault zone, southern Sierra Nevada, California, U.S.G.S. Bulletin, 1651, 25 pp.

Saleeby, J.B. and Busby-Spera, C., 1993, Paleogeographic and tectonic setting of axial and western metamorphic framework rocks of the southern Sierra Nevada, California, in Mesozoic Paleogeography of the Western United States – II, eds., Dunne, G.C. and McDougall, K.A., Pacific Section SEPM, Book 71, 197-226.

Scholz, C. H., 2000, Evidence for a strong San Andreas fault, Geology, 28, 163-166.

Shea, W.T. and Kronenberg, A.K., 1993, Strength and anisotropy of foliated rocks with varied mica contents, Journal of Structural Geology, 15, 1097-1121.

Wintsch, R.P., Christoffersen, R., and Kronenberg, A.K., 1995, Fluid-rock reaction weakening in fault zones: J. Geophysical Research, 100, p. 13,021-13,032.

Zoback, M. D., Zoback, M. L., Mount, V. S., Suppe, J., Eaton, J. P., Healy, J. H., Oppenheimer, D. H., Reasenberg, P. A., Jones, L. M., Raleigh, C. B., Wong, I. G., Scotti, O., and Wentworth, C. M., 1987, New evidence on the state of stress of the San Andreas fault system: Science, v. 238, no. 4830, p. 1105-1111.

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Reports Published

Chester, J. S., 2001, Structure and petrology of the Kern Canyon fault, California: A deeply exhumed strike-slip fault, Final Technical Report, USGS# 00-HQ-GR-0029.

Neal, L A., Chester, J. S., Chester, F. M., Wintsch, R. P., 2000, Internal structure of the Kern Canyon fault, California: A deeply exhumed strike-slip fault, EOS Trans. AGU, Fall 2000 meeting.

Neal, L.A., 2001, Internal structure of the Kern Canyon fault, California: A deeply exhumed strike-slip fault, M.S. Thesis, Texas A & M University, in prep.

Non-Technical Summary

In order to reduce the loss of life and property as a result of the occurrence of large-magnitude earthquakes, we must increase our understanding of the physical and chemical processes that govern repeated earthquake generation along large-displacement continental fault zones. Geologic field investigations of large-displacement faults that are exposed at the Earth's surface offers a cost-effective way to investigate the internal structure, mineralogy, and chemistry of fault zones in detail, and is complementary to other approaches such as deep drilling and geophysical (indirect) imaging. We will use a variety of techniques in the laboratory to analyze rocks collected in the field. These data will be used to help constrain and test existing hypotheses for fault weakening and earthquake generation. In addition, data gathered from this study will help guide future field, experimental, and theoretical investigations of the earthquake process.