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

USGS Award No: 00HQGR0029 (TAMU)
Annual Project Summary

Judith S. Chester
Texas A & M University
Department of Geology and Geophysics
College Station, TX 77843
Tel: 979-845-1380; Fax: 979-845-6162
e-mail: chesterj@geo.tamu.edu

Program Element: II

Key Words: Geologic mapping, source characteristics, tectonophysics, fault dynamics

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. 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 a 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 2; 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, 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). Correlation of offset plutonic and metamorphic rocks across the KCFZ suggests dextral separation of approximately 15 km in the vicinity of Lake Isabella (Ross, 1986; Moore & du Bray, 1978).

At Engineer Point, the fault consists of a broad fractured and mineralogically altered damage zone several hundred meters thick (Figure 2; Ross, 1986). Previous work indicates that the zone displays extensive retrograde alteration primarily involving the transformation of feldspars to mica, quartz, and calcite. Results of our study to date show that the Kern Canyon fault records strike-slip deformation at lowermost greenschist facies, and contains intermingled cataclastic and phyllonite shear zones. In addition, there are numerous quartz and calcite veins within the fault zone, some of which display alteration halos, that record fluid-rock reactions and focused fluid flow. 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.

Research for FY2000 will provide an overall characterization of the macroscopic structure and petrology of the KCFZ at Engineer Point, and additional detailed microstructure and petrologic characterizations of the phyllonitic rocks in the zone. The initial petrologic study, primarily using optical microscopy and microprobe analysis, has focused on determining the syndeformation mineral-chemical reactions, and evolution in time of deformation and mineral reactions relative to the mesoscopic field relations. At the end of this contract period, we should have a detailed description of the phyllonite that includes a characterization of the spatial variation in fracturing at the microscopic scale, quantitative data demonstrating the extent and types of feldspar alteration reactions to mica, and a preliminary description of fracture-healing, neomineralization, and plastic deformation of quartz. Our plans for the renewal period (FY2001, 2002) will focus on 1) furthering our understanding of the chemical system and deformation mechanisms for phyllonite formation, 2) the origin of the cataclasites relative to the phyllonites, and 3) the role of localized slip during deformation.

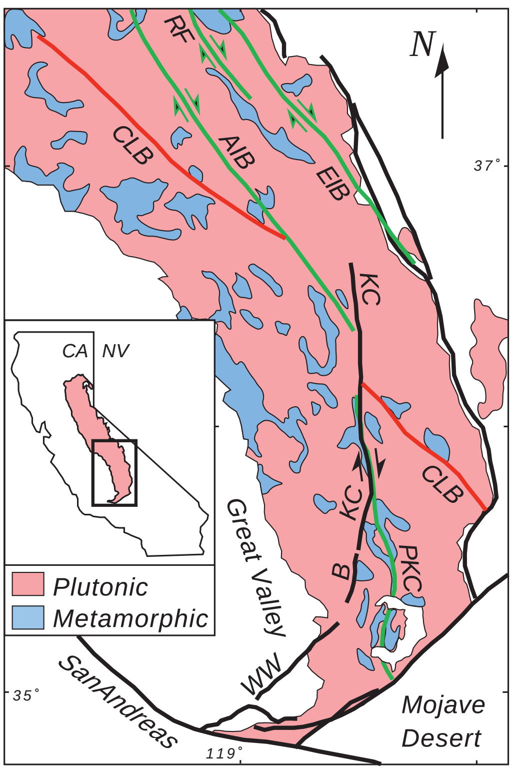

Figure 1. Map of the southern Sierra Nevada batholith showing the location of the Kern Canyon fault zone (KC) relative to other tectonic features, including the axial intrabatholithic break (ABI), cryptic lithospheric boundary (CLB), eastern intrabatholithic break (EBI), proto-Kern Canyon fault (PKC),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

Results

Fault rock structures, relative intensity of hydrothermal alteration, and protolith rock type have been mapped over Engineer Point at a scale of 1:6000 (Figure 2). Mesoscopic scale fracture density traverses 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 have been collected and sectioned, and preliminary optical microscopy and quantitative microprobe analyses have been performed.

Through field mapping we have documented that the KCFZ 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 N20E and contains breccias, foliated cataclasites and ultracataclasites, and displays prominent 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 (e.g., Chester et al., 1993; Chester and Chester, 1998) in that it consists of a broad zone of fractured and altered rock bounding a relatively narrow core of highly sheared and comminuted fault rocks. Although locally variable in thickness and deformation intensity, the damage zone generally displays an ordered progression of mesoscopic scale structures recording increased deformation towards the fault core. Quartz and calcite fracture-fill is common in the damaged zone, 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. Within the fault zone, the veins and shears are steeply dipping to vertical, and have a preferred NE strike forming acute angles with the main cataclastic zone. Offset of veins by subsidiary shears indicates right-lateral separation. The orientations and offset of features all are consistent with overall right-lateral, strike-slip separation by the cataclastic zone.

The dominant cataclastic zone is cut by faults formed during the second phase of brittle deformation. These 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.

The phyllonite zone trends N40E to N20E, and is located on the west side of the cataclastic zone. To the south, the phyllonite is spatially separate and is relatively undisturbed. It is cut by the cataclastic zone in the central portion of the peninsula. Therefore it is possible to follow the phyllonite northward and observe the progressive effects associated with cataclastic overprinting. The phyllonite zone is on the order of 10 m wide having gradational deformation boundaries. S-C' fabrics indicate right-lateral oblique shear with the east side up. Quartz C-axis fabrics imply low-temperature basal glide and that dynamic recrystallization of quartz occurred during phyllonite formation. Similar faulting relations are evident north of Kernville where the Kern Canyon fault follows the trace of the PKCFZ (e.g., Busby-Spera and Saleeby, 1990; Saleeby and Busby-Spera, 1993). However, the relation of phyllonitic ductile shearing at Engineer Point to the PKCFZ is unknown.

Zones of chemical alteration roughly correlate with the damaged zone of the faults. Rocks with the greatest degree of alteration occur closest to the fault cores and close 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.

During the first part of the FY2000 contract period we have focused our microstructure and petrologic study on a suite of samples collected along a traverse from the undeformed protolith (Wagy Flat granodiorite) to the center of the phyllonite zone. The protolith is a coarse-grained granoblasitc rock composed of zoned plagioclase (An_{40-45} cores to An_{25} rims), potassium feldspar, biotite, quartz,

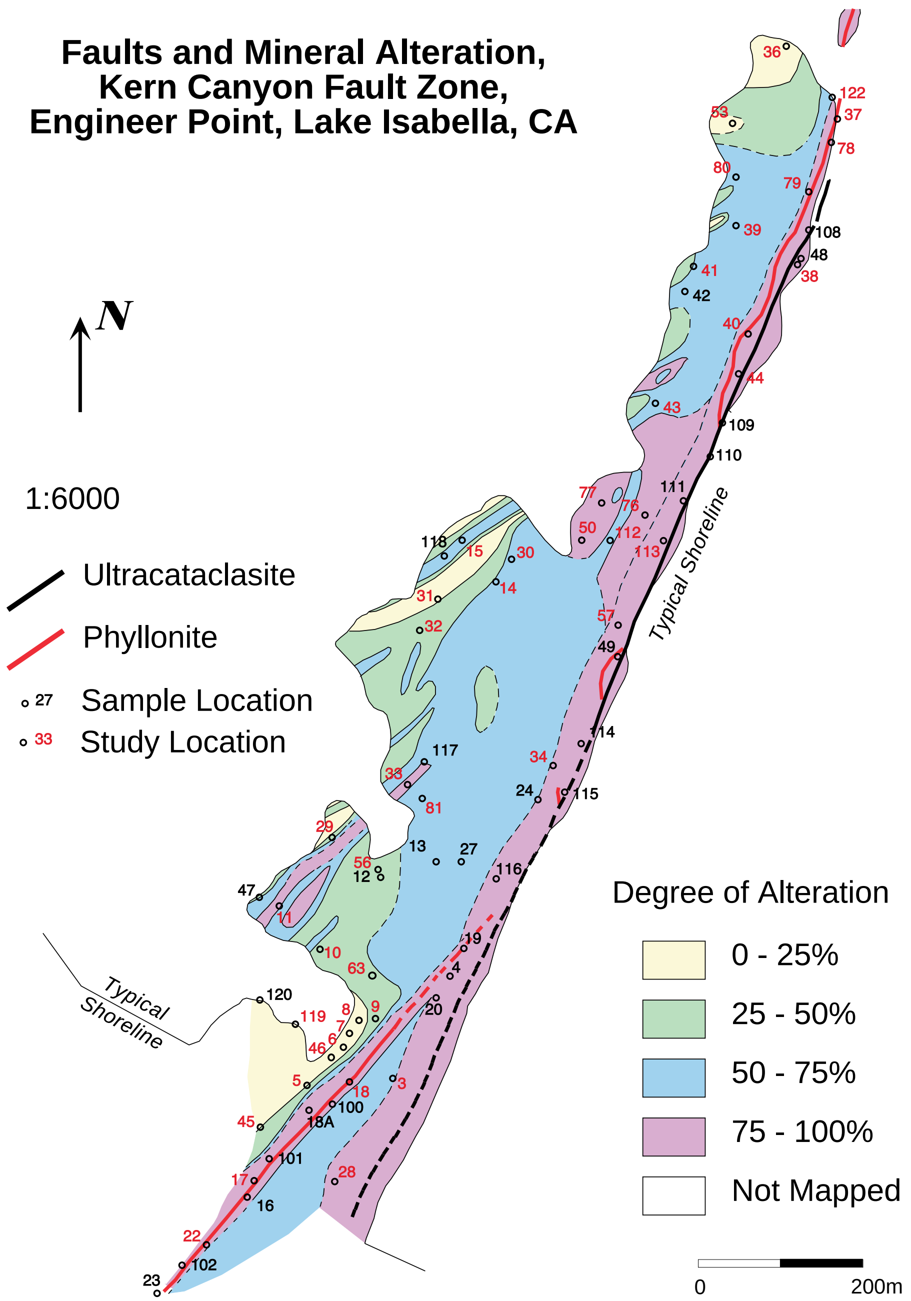

Figure 2. Map of Engineer Point, Lake Isabella, CA showing the relative volume of rock that has undergone fault-related alteration reactions.

sphene and minor amounts of hornblende. At the microscopic scale the quartz grains display a relatively low density of intragranular microfractures, and biotite crystals are slightly undulose. Within the damage zone of the phyllonite we can distinguish four domains that display distinct deformation characteristics and chemical reaction products. Within these domains we see a progression of alteration towards the fault core. Preliminary quantitative microprobe analyses of the outermost domain of the damage zone show that this zone is characterized, in part, by the pseudomorphic replacement reactions of anorthite to albite ($An_{02\text{-}00}$)+muscovite+calcite; biotite to vermiculite, and sphene to rutile+quartz. In the 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), 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.

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. Over the FY2000 period we will continue to work out the mineral reactions within each structural domain to identify the key element exchange reactions. Ultimately, however, it will be necessary to gather the whole-rock chemical data planned for the renewal period to determine to what extent and at what scale the fault system was open or closed.

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., and Chester, J.S., 1998, Ultracataclasite structure and friction processes of the Punchbowl fault, San Andreas system, California, Tectonophysics, 295, p. 199-221.

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.

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.

Webb, R.W., 1936, Kern Canyon fault, southern Sierra Nevada, Journal of Geology, 44, 631-638.

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.

Reports Published

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.