THE STRUCTURE AND COMPOSITION OF EXHUMED FAULTS, AND THEIR IMPLICATIONS FOR SEISMIC PROCESSES

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ABSTRACT

Field studies of faults exhumed from seismogenic depths provide useful data to constrain seismologic models of fault zone processes and properties. Data collected on the San Andreas Fault in the San Gabriel Mountains has shown that large-displacement faults consist of one to several very narrow slip zones embedded in a cataclastically deformed sheared region several meters thick. However these faults have not been buried to depths greater than 5 km. Fault zones in the Sierra Nevada, California allow us to study the microstructures resulting from the deformation mechanisms active at seismogenic depths. Syn-fault mineralization shows that these left-lateral strike-slip faults formed at 5-12 km depth. Detailed microstructural analyses of the small faults reveal that they evolved from cooling joints filled by chlorite, epidote and quartz. These joints were then reactivated to form shear faults with accompanying brittle fracture and cataclastic deformation, ultimately developing very fined-grained cataclasites and ultracataclasites. The shear-induced microstructures are developed on faults with as little as several mm of slip showing that narrow slip-surfaces develop early in the lifetime of these faults. Subsequent slip has little effect on the microstructures. The inferred similarity of deformation mechanisms in faults 10 m to 10 km long indicates that basic slip processes on the faults are scale invariant, and may be a cause for the inferred constant b-value for small earthquakes. Analysis of map-scale fault linkages and terminations indicate that linkage zones are up to 400 m wide and 1 km long, and consist of altered and fractured rocks with numerous through-going slip surfaces. Terminations are regions of numerous splay faults that have cumulative offsets approaching those of the main faults. The slip distribution and structure of the terminations and linkage zones suggest that seismic slip may propagate into these zones of enhanced toughness, and that through-going slip can occur when a sufficient linkage of faults in the zone allow slip to be transmitted.

INTRODUCTION

Numerous questions in earthquake seismology, and earthquake mechanics in general, involve aspects of fault zone structure and composition. A partial list of subjects discussed at the Third Conference of Tectonic Problems of the San Andreas Fault (SAF), and in the recent literature that involve the physical properties and structure of faults includes:

a. The width of the fault zone that slips during an earthquake, and along which aftershocks are distributed, appears to be very narrow (*Nadeau and McEvilly*, 1997) and aftershock data surrounding strike-slip faults of the SAF system often display off-fault focal mechanisms that are different than the main shock mechanism (*Oppenheimer et al.*, 1988).
b. Some faults exhibit long streaks of micro-earthquakes (*Rubin* et al., 1999), typically sub-parallel to the net slip vector on the fault.
c. Fault zone seismic waves resolve fault structure at depth, and suggest fault zone widths of 100-300 m. Headwaves traveling at interfaces between fault zone components of different moduli, trapped waves traveling within a low-velocity zone produced by aftershocks (*Li* et al., 1994) or explosions (*Li* et al., 1999), and internally reflected waves can all be used to image the structure of the fault. However care must be used in interpreting seismograms for such waveforms (*Igel* et al., 1997; *Ben-Zion*, 1998). The results of these studies indicate that fault zone structure is relatively uniform at depth (*Igel* et al., 1997).

d. Seismic tomographic studies image the fault zones, and help identify regions of velocity contrast in and around faults 500 – 2 km thick (*Eberhart-Phillips and Michael*, 1993) but do not image the finer scale fault zone structure (*Igel* et al., 1997). Analyses of resistivity across the SAF also indicate a broad region up to 1 km thick (*Unsworth* et al., 1999).
e. Lateral variations of the frictional properties of faults have been called on to explain the slip-weakening behavior of some faults (*Boatwright and Cocco*, 1994, 1996) or the slip arrest behavior of others (*Nicholson and Lees*, 1992).
f. Some models for the behavior of ruptures suggest asperities along the fault surface help to generate a localized stress concentration, where ruptures may nucleate (*Aki*, 1992).
g. Rupture propagation processes, whether as a self-healing slip patch (*Heaton*, 1990) a propagating crack (*Harris and Day*, 1999), or as a slip pulse (*Andrews and Ben Zion*, 1997) typically require that there is a significant moduli contrast between fault zone and protolith.
h. Numerous earthquakes display a lack of correlation between the deep slip patterns and those observed at the surface (*Wald and Heaton*, 1994). Mechanisms for this include stress variation, dynamic stress effects on the propagation of slip and energy radiation by a fault zone to the surface (*Brune and Anooshopoor,* 1998) or the presence of weak fault materials near the earth's surface resulting in earthquakes that produce little surface slip (*Scholz,* 1990).
i. Some ruptures stop after short slip distances but others are able to propagate across geometric complexities such as bends, branches, and steps (*dePolo* et al., 1991). *Harris and Day* (1999) suggest that secondary earthquakes can be triggered by the first rupture whereas *Ellsworth and Beroza* (1995) suggest that the ultimate size of a rupture is controlled by a priori earthquake energy.
j. Curved or irregular slip distributions could be produced by heterogenous stress state orientations on the fault surface (*Bouchon* et al., 1998; *Spudich*, 1992) or by the change of fracture mode at fault tips (*Martel and Boger*, 1998).
k. The relative strength of the SAF, and the causes of the weak, low heat flow behavior remain enigmatic (*Hickman* 1991).

For all the issues enumerated above, characterization of exhumed faults can provide insights by 1) yielding physical evidence to support different models or interpretations, and 2) conditioning modeling and data inversion to constrain the mechanical problem. In this brief contribution we summarize recent work on exhumed faults of the San Andreas Fault system, and then present data from faults exhumed from seismogenic depths from the Sierra Nevada, California. These field studies have allowed us to examine the processes of slip localization, the structure of fault zones, the linkage and termination of faults, and the distribution of slip and slip vectors on large faults.

EXHUMED SAN ANDREAS FAULT STRUCTURES

Studies of exhumed faults in the SAF system suggest that, at least to depths of 5 km, large-displacement faults consist of one to several very narrow slip zones embedded in a cataclastically deformed sheared region several meters thick. *Waters and Campbell* (1935) and *Oakshott* (1958) were the first to show that the SAF is characterized by a narrow (<10 cm) band of very fine-grained fault rock, and *Anderson and Osborne* (1983) revealed some of the microstructures and geochemistry of this zone. *Chester and Logan* (1986) described the mechanisms of ultracataclasite development in the San Gabriel Mountains, and presented the fault core-damaged zone model for faults. The thin fault core lies within a damaged zone that may be up to several hundreds of meters thick, consisting of small faults, open fractures, and veins, that typically have orientations at high angles to the main slip surface (*Schulz and Evans*, 2000). This model was tested and refined by *Chester* et al., 1993; *Evans and Chester*, 1995; *Schulz and Evans*, 1998; *Chester and Chester*, 1998; and *Schulz and Evans*, 2000. The damaged zone commonly exhibits a high degree of alteration, and is a region of enhanced permeability and reduced elastic moduli. *Schulz and Evans* (2000) suggest that the various geophysical methods of defining the width of fault zones use wavelengths that are tuned to different parts of the fault structure.

While providing insight into some aspects of the morphology and behavior of seismogenic faults, the work on exhumed faults of the SAF captures the result of processes only at the upper part of the seismogenic zone. This data has generally been collected from rocks that have been exhumed from above depths where earthquakes nucleate. In this paper, we attempt to do this by summarizing recent work on exhumed left-lateral strike-slip faults in the Sierra Nevada, California that have been exhumed from depths of 5-12 km.

EXHUMED FAULTS IN THE SIERRA NEVADA

Small left-lateral strike-slip faults in the central Sierra Nevada (Figure 1) have long been used as a natural laboratory for the study of faults. Much of the previous work on the small strike-slip faults of the Sierra Nevada has focused on fault mechanics (cf. *Segall and Pollard* 1983; *Martel* et al., 1988; *Martel*, 1990). *Segall and Pollard* (1983), *Segall* et al., (1990) show several photomicrographs of fault zone microstructures, but only S*egall and Simpson* (1986) and *Christiansen and Pollard* (1997) discuss the origin of the microstructures in detail. Here we discuss the microstructures related to map-scale structures, and larger scale fault geometry for these faults which have been exhumed from seismogenic depths.

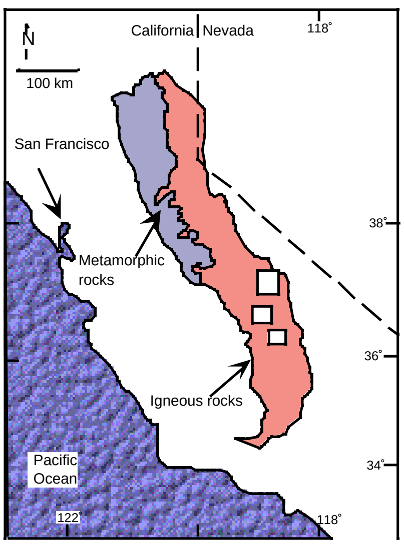

Figure 1. Location map of study areas.

The ENE-trending faults are thought to have formed from cooling joints developed during the waning stages of Late Cretaceous plutonism (*Bergebauer and Martel*, 1999). These joints contain epidote, quartz, sericite and muscovite mineralisation, making them weaker than the granite protolith and therefore prone to reactivation as shear fractures. Regional dextral transpressive shearing (*Tikoff and Saint Blanquat*, 1997) or stress reorientation (*Martel* et al., 1988) resulted in left lateral slip on some of the joints and the formation of fault zones. Slip was accompanied by mineralization (quartz veins) along the faults. The uniform composition of the granitic protolith and the presence of numerous dikes in the area allow detailed analyses of slip and deformation patterns in and around the faults. Additionally, the high amount of topographic relief provides opportunities to determine the spatial distribution of slip and fault-rocks on the fault partially in the vertical dimension as well as horizontally.

The faults in this study range from trace lengths of 10’s m with 10’s cm of slip, to faults over 10 km long with over 100 m of slip. The smallest faults discussed here have trace lengths of 10-30 m and so, if slipped over their entire surface, represent faults that could produce M_0 to M_1 earthquakes with seismic moments of 10^9 –10^{11} Nm. The largest faults described here are segmented structures, where each fault segment could represent a M_4 earthquake; if the entire 10 km fault slipped, it would create a M_5-M_6 earthquake. The dominant deformation mechanisms are brittle to brittle-plastic and are considered to be active at depths of 5-12 km. Geobarometry and geothermometry give additional evidence for the depth of fault formation (*Lim* 1998). Mylonitic foliations associated with these structures indicate that brittle and semi-brittle slip localization is compatible with temperatures at or above 300°C. Thus these faults formed as a result of accumulated seismic slip near the base of the seismogenic zone.

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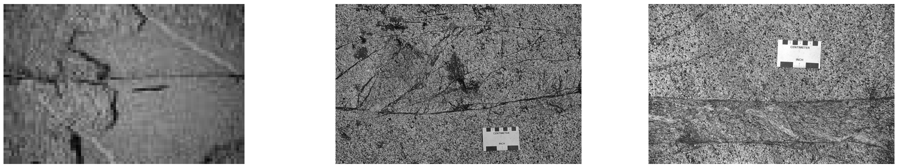

Figure 2. Three outcrop photos of small faults. A). Narrow fault with chlorite-gouge and pure brittle slip. B) Horsetail splay faults at dilational fault tip. C) Quartz-filled fractures, narrow faults, and mylonitic foliation developed along a fault.

Our examination of small faults (<40 m) in the Kip Camp and Bear Creek areas (*Lim*, 1998) and of a 120 m long fault with 4 m of slip (*Robeson*, 1998) reveal that the fault surfaces are marked by foliated chlorite-epidote-quartz zones 1-4 cm thick (Figure 2), similar to those found by previous workers. Detailed microstructural analyses of the small faults reveal their evolution from brittle Mode I fracture (cooling joints) filled by chlorite, epidote, and quartz (Figure 3a), through brittle fracture and cataclastic deformation (Figure 3), to the development of very fined-grained cataclasites and ultracataclasites (Figure 3). The shear-induced microstructures are developed on faults with as little as several mm of slip (Fig. 3), and the transition to the foliated textures may occur with as little as 10-20 cm of slip. Fault surfaces with chlorite-epidote-quartz assemblages display a well-developed foliated texture and thin dark regions that represent a narrow slip zone. The larger-displacement Gemini faults, with displacements of up to 140 m, have very similar microstructures (*Pachell and Evans*, submitted). Textures of the fault-related rocks include mm to cm thick bands of cohesive cataclasites and breccias, sericite-lined fractures and shear zones, and sericite-chlorite shear zones.

Figure 3. Thin section photographs showing the narrow fault zone (left) with approximately 30 cm of slip, and a foliated cataclasite (right) on a fault with ~1.2 m of slip.

Whole-rock geochemical analyses of these faults show subdued, but notable, changes with respect to the host rock. The small faults exhibit a 1-3 wt % reduction in SiO_2, and small increases in MgO, CaO and TiO_2. Similar, but much larger, geochemical changes have been documented for faults of the SAF system (*Evans and Chester*, 1995) and are interpreted to be the result of reactions that take place in the fault zone while it is active. The transformation of feldspars to micas and hornblende and biotite to chlorite that are seen in thin section are reaction softening mechanisms (*Evans*, 1988; *Wintsch* et al., 1995) that result in a weakening of the fault zone lithology.

Thus, we suggest that slip on faults that form at depths of 5-12 km, in an environment that promotes hydrolysis reactions, seems to localize VERY early, and that strain softening mechanisms associated with hydrothermal and reactive fluids may be activated in the earliest stages of faulting. *Power* et al. (1988) suggest that abrasive wear would dominate along a fault surface as long as asperities were present. Once asperities are ground off, stable fault textures would develop. We suggest that these reaction-weakening mechanisms, in conjunction with the development of fractures in the rocks and the wearing off of asperities, may be relatively easily activated, and that slip localization would occur very early in a fault's history. Such a history is likely in the case of the Sierran faults, where the faults nucleated on pre-existing Mode I joints.

Fault Linkage and Termination

Numerous workers (*Sibson*, 1986, 1987; *Scholz*, 1990; *King and Nabelek*, 1985) have suggested that fault segments and fault terminations are typically characterized by regions of complex fault distributions, and that these regions may be areas where earthquakes nucleate or terminate. Much of the detailed examination of segments, fault tips, and step-overs has been in shallowly buried sedimentary rocks (*Peacock and Sanderson* 1991, 1994) or where faults were active at the surface (*Trudgill and Cartwright* 1994, *Cartwright* et al. 1995a and b, *Dawers and Anders* 1995). *Sibson* (1987) presents maps from subsurface mine workings that suggest that bends and terminations in bedrock may be replicas of the splay structures observed in the surface rupture patterns of recent faults. Examination of the structure and processes at fault segment boundaries is important for understanding the processes of fault propagation, termination, and what ultimately controls the size of an earthquake (*Harris and Day*, 1999; many others). This is well-documented for the 1992 Landers earthquake, which started on one fault segment and jumped across two left-steps to create a large earthquake (*Wald and Heaton*, 1994). To evaluate the possible structure and the composition of linkage zones of faults at seismogenic depths, we briefly summarize the results of our analysis of linkage along a 10 km long fault zone in the Sierra Nevada.

Pachell and Evans, (submitted) presents a detailed structural analysis of the Gemini fault, which has a total trace length of 9.3 km, and a maximum slip of 140 m (Figure 4). The fault consists of three segments, each joined by a complex zone of faulting up to 400 m wide and 1 km long. Each zone consists of numerous faults that strike up to 30° to the main trace of the fault. These zones of complex faulting and fracturing appear to be associated with local slip minima and thus may represent exhumed fault segments. As in the case of the much smaller faults, the rocks of these zones appear much more altered and fractured than those adjacent to the main traces of the fault.

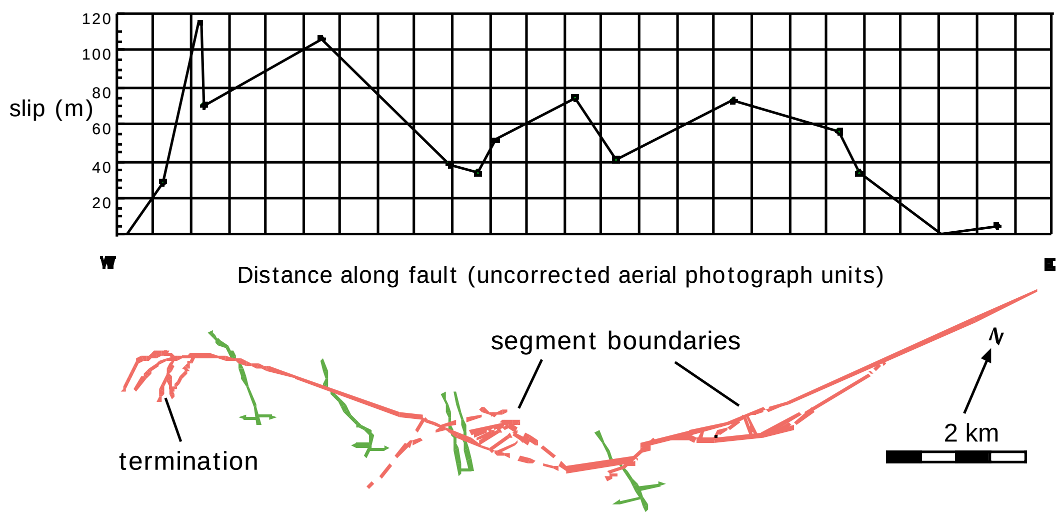

Figure 4. a) slip distribution on the Gemini fault. b) Simplified map of the Gemini fault, showing complex fault geometries at presumed segment boundaries. Green lines indicate contacts offset by fault. From Pachell and Evans, submitted.

At terminations of the smallest faults, open-mode fractures are filled with quartz, or are associated with regions of mylonitic foliation (Figure 2b), (*Lim* 1998; *Christiansen and Pollard*, 1997). The splay fractures around the fault tips form dihedral angles of 30-45° to the main fault (Figure 2c), similar to the results of *Granier* (1985) and much lower than the 70° predicted from linear elastic fracture mechanics models of stresses at crack tips (*Pollard and Segall*, 1987). The low splay angles suggest that a cohesive zone exists at the edges of the faults (*Ida*, 1972; *Martel*, 1997; *Cooke*, 1997; *Martel and Boger*, 1998). These regions may scale to be roughly 0.05 to 0.1 of the fault diameter, and taper to very small sizes at the top and bottoms of the starting joints (cf. *Martel and Boger*, 1998; *Hestir* et al., in press). The Gemini fault terminates at its west end in a curved trace (Figure 4) that is up to 40° from the main trace. The fault terminates into 3 splays 300-500 m long, which have slip vectors that plunge shallowly west (*Pachell and Evans* submitted) (Figures 4 and 7).

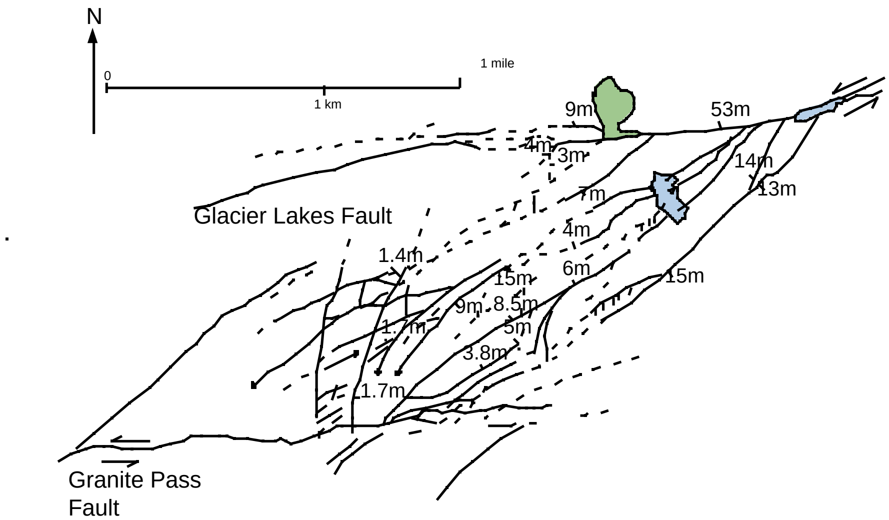

Figure 5. Simplified geologic map of the Glacier Lakes fault, Kings Canyon National park, California. Numbers indicate slip measured on faults.

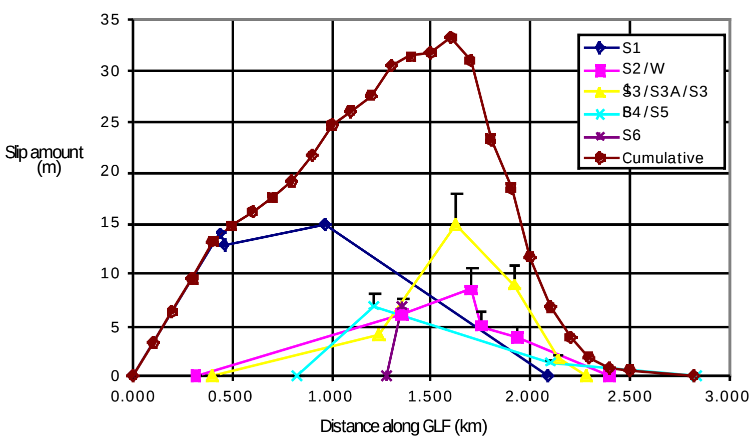

Figure 6. Slip measured on individual splays of the Glacier Lakes fault, and cumulative slip for all faults measured.

The Glacier Lakes fault in Kings Canyon National Park (*Evans* et al., 1999) is a nearly pure left-lateral, strike-slip fault with ~55 m of slip in its western end (Figure 5). The fault is nearly vertical, strikes N 75° E. The map pattern at the eastern end of this fault suggests a left-stepping zone of “horsetail” faults connecting the Glacier Lakes fault to the Granite Pass fault. However based on petrologic and structure observations we feel the Granite Pass fault is an older fault and is not kinematically linked to the Glacier Lakes fault. The Glacier Lakes fault may in fact terminate because of the presence of the Granite Pass fault. Splay faults emanate from the Glacier Lakes fault and strike at 20-40° to the main slip surface (Figure 5). The trace of the main fault appears to overshoot the splay fault region and terminate 3 km west of the splay faults, again in a broad arc that turns to the southwest. Slip on the Glacier Lakes fault decreases markedly beyond the splay faults. The amount of slip on individual splays varies, with most of the splays reaching their maximum slip near the main Glacier Lakes fault. While each fault exhibits variability, the cumulative slip across all of the splays has a smooth triangular profile (Figure 6), similar to that documented for single fault strands (*Cowie and Shipton*, 1998). This might suggest that slip can be transferred from the main fault to individual splays in a seemingly random fashion, but that over time, the cumulative slip on the main fault is at least partially bled off to the splays.

The general nature of the fault zone at these tips and step-overs is one of a highly fractured and faulted rock mass, with numerous zones of enhanced mineralization. These regions are local zones of dilatancy (*Sibson*, 1987) where pore fluids would like flow both in the static and dynamic fault modes. Thus, the segment boundaries are likely to be regions of reduced elastic moduli (*Bruhn* et al., 1990) and only when the narrow slip surfaces form and are connected can slip "jump" from one quasi-planar fault segment to another.

Slip vector variations

In both the Gemini and Glacier Lakes region, slip on the fault surfaces has variable orientations. The Gemini fault has up to 90° of variability in rake angles along any individual segment (Figure 7), although most range ± 30° of horizontal. There is no clear pattern regarding the distribution of slip; steeper rakes occur at the centers of segments as well as towards the segment boundary zones. In the Glacier Lakes area, slip vectors on the main fault are relatively constant and the slip vectors on the splay faults tend to plunge more steeply away from the main fault (Figure 8).

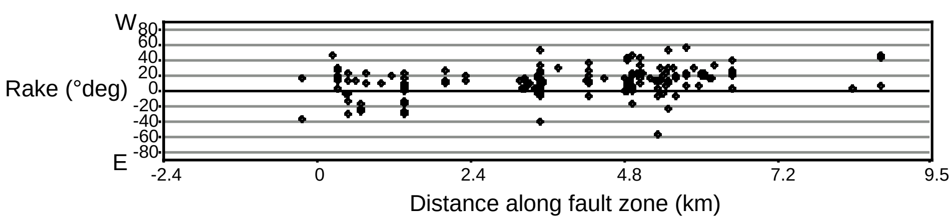

Figure 7. Rakes of slip vectors measured on the Gemini fault.

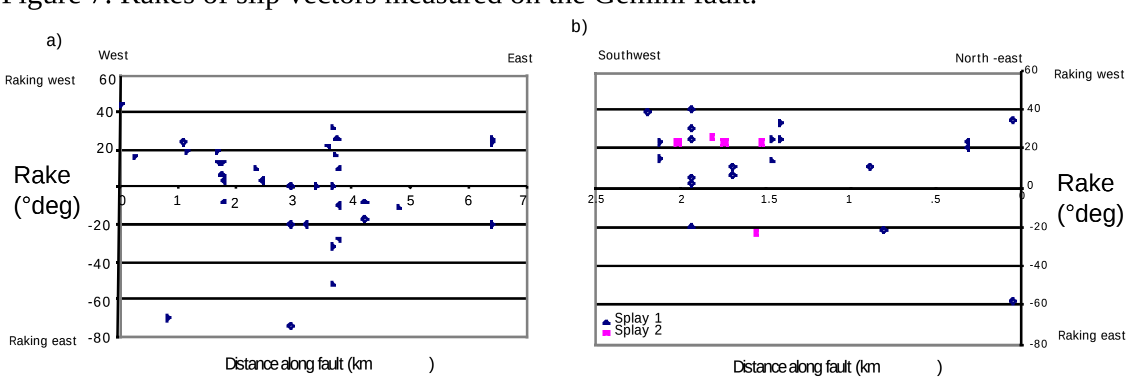

Figure 8. a) Slip vector rakes on the main trace of the Glacier Lakes fault, and b) along splays of the fault.

DISCUSSION

How do our observations relate to the topics raised at the beginning regarding the processes of seismic slip on faults? We have shown a range of fault zone structures that provide constraints on the structure of seismically active faults at depth, and also provide insights into processes of slip accumulation. Our work shows that exhumed faults in the San Gabriel Mountains (*Chester* et al., 1993; *Chester and Chester*, 1998; *Schulz and Evans*, 2000) and the Sierra Nevada (*Lim*, 1998; *Robeson*, 1998; *Evans* et al., 1999; *Pachell and Evans,* submitted) consist of one to several narrow slip-surfaces on which the majority of slip is accommodated. Microstructural analysis shows thin zones of fine-grained cataclasite fault rocks with thin slip-surfaces several mm thick, evolving into thin regions of ultracataclasites. Strain localization is assisted by reaction softening and phyllosillicate-dominated slip. The same microstructures (and hence deformation mechanisms) are seen on the faults with largest slips as well as on the smallest faults. While the damaged zone adjacent to the fault varies in size from smaller to larger faults, thickness of the fault core is relatively constant.

These microstructures are remarkably similar to faults seen on the San Gabriel and Punchbowl faults, where displacements are up to 44 km. *Gay and Ortlepp* (1979) documented a similar development of mature fault microstructures in situ, in which brecciation and brittle grain size reduction occurred for faults with 60-120 mm of slip. We suggest that these field data show that slip nucleates very early on in the evolution of the fault rock and that further displacement is accommodated by reusing and reworking the existing slip-surfaces. The evolution from fine-grained cataclasite to ultracataclasites presumably occurs due to repeated slip on each slip surface. A similar conclusion was reached by *Shipton and Cowie* (submitted) in their study of shallow fault rocks in high porosity sandstones, suggesting that the mechanism of early slip localization does not only apply to crystalline host rocks.

The direct shear experiments of *Yund* et al. (1990) and *Beeler* et al. (1996) showed that well-developed shear fabrics form with only mm of displacement, and subsequent slip is often accommodated by the development of stable microstructures that include foliated cataclasites and ultracataclasites, and the creation of a narrow slip zone, typically at the margin of the small fault. Experimental shearing of phyllosilicate-rich gouge in an environment where slip in phyllosilicates and pressure solution is promoted also show that slip may be localized very early in the history of the system, and leads to a strain weakening response (*Bos et al.*, in press). The similarity in textures, and thus the inferred similarity of deformation mechanisms in faults 10 m to 10 km long, indicates that the basic slip process on the faults are scale invariant. Thus, the nearly constant stress drops and constant b values documented by *Abercrombie* (1995, 1996) are interpreted to be a result of the same fundamental deformation mechanisms of slip acting over increasing areas with larger faults.

An increasing body of field study data (*Lim*, 1998; *Robeson*, 1998; *Evans* et al., 1999; *Ohtani* et al., 2000; *Pachell and Evans,* submitted, *Shipton and Cowie* submitted) is showing that the majority of fault strain is accommodated on very narrow slip-surfaces. These data agree with available seismological data (*Nadeau and McEvilly,* 1997). The development of thin slip surfaces and fault core zones is favored from mechanical and thermal modeling basis (*Chester*, 1995; *Mori*, pers. comm., 2000) Thermal-mechanical calculations suggest that fault slip is required to be focused on narrow surfaces; otherwise the amount of work needed to be done, and the amount of heat generated by a rupture, exceeds that available in earthquakes.

We also examine segment boundaries across a range of fault zone sizes. We show that at seismogenic depths, segments are characterized by numerous faults, open fractures and hydrothermal alteration. The orientation and density of faults in the segment boundary zones are similar to those observed at the surface (cf. *Sibson*, 1987; *Peacock and Sanderson* 1991, 1994, *Trudgill and Cartwright* 1994, *Cartwright* et al. 1995a and b, *Dawers and Anders*

1995). The segment boundaries and terminations observed here may represent regions of high fracture toughness, in which the high degree of alteration and fracturing inhibits propagation of tensile fractures. On the Glacier Lakes fault the random slip distribution on individual splays but smooth cumulative slip profile indicates that seismic slip may propagate into this zone of enhanced toughness, and that through-going slip can occur when sufficient faults in the linkage zone are connected and transmit slip. Thus, ruptures may break through these knots of geological complexity if the geometry or kinematics are favorable (*Harris and Day*, 1999).

Slip vector orientations vary significantly along the length of the Gemini fault, and do not seem to vary systematically with position along the fault. Conversely, slip vectors on the Glacier Lakes fault appear to change from nearly pure strike-slip to oblique slip towards the termination. Oblique slips have also been seen near the terminations of, and segment boundaries on, surface ruptures of active normal faults (*Wu and Bruhn*, 1994; *Roberts*, 1996a and b) and shallow exhumed normal faults (*Shipton and Cowie* submitted). These observations could be explained by the prediction that shear fractures tend to die out into different modes near their terminations (e.g. *Martel and Boger* 1998). The variations in slip vector orientations at the same point on the fault may represent the effect of different slip patches having ruptured at different points on the fault (*Roberts*, 1996a; *Shipton and Cowie*, in prep.). *Cowie and Shipton* (1998) present a model of fault growth by repeated slip to explain the observation that cumulative fault displacement profiles are triangular in shape. While the slip profiles of individual earthquakes are often much more complex (e.g. *McGill and Rubin*, 1999), when the ruptures that have occurred on the lifetime of a fault are summed the end result is a triangular slip profile across the whole fault. If each rupture has a variation in slip vector orientations like that predicted by *Martel and Boger* (1998), and subsequent slip-episodes do not obliterate each generation of slip vectors, then the slip vector orientation at one point would be highly variable (*Roberts* 1996a; *Shipton and Cowie*, in prep.), which could explain the data from the Gemini fault. Some workers have suggested that varying slip vector orientations may be due variations in stresses on faults, due in part to variations in fault composition (*Bouchon* et al., 1998, *Spudich* 1992). However, our work shows that the fault composition may be uniform over a large range of scales.

Away from fault tips and segment boundaries there is little or no deformation that would correspond to a fault damage zone around the Sierran faults. *Scholz* et al. (1993) proposed that fractures that enable the fault tip to propagate through undeformed rock at the fault tip form a fault-tip process zone. They postulated that these fractures nucleate within a region of high stress at the fault tip that scales with the size of the fault. As the fault grew in length and displacement, the tip would propagate and a wake of “paleo process zone” fractures would be seen adjacent to the fault. The fact that this wake of fractures is not seen for the Sierran faults, may be a function of the faults nucleating on pre-existing joints. *Martel* (1990) described an evolution for these faults from simple faults, which were re-activated joints, through complicated fault zones that consist of segments of individual joints connected together. If there is a pre-existing plane of weakness, it may not be necessary for the faults to have grown by radial propagation. Instead displacement accumulation occurs primarily within the very narrow slip-surface within an individual reactivated joint until such a point that it reaches out and links with an adjacent small fault. At this point host rock will be freshly deformed and complex linkage structures will form.

The structures at the fault tips in the Sierras are consistent with faults that did not grow by radial propagation. The models of *Martel* et al. (1990) assume displacement accumulation on a surface that does not propagate into the surrounding rock and reliably predict the orientations of the splay fractures seen in the field. However in other lithologies faults may have grown by a more complex process in more or less intact rock (i.e. *Shipton and Cowie* submitted). This could lead to a very different relationship between the fault core, damage zone and structures at terminations and segment boundaries. We therefore recommend that when applying this field data to subsurface portions of seismic faults, care is taken in extrapolating into different lithologies.

CONCLUSIONS

1) Data from exhumed SAF faults in the San Gabriel Mountains show that a narrow fault core is surrounded by a wider zone of damage. These faults were exhumed from a depth of less than 5 km.
2) Faults exhumed from seismogenic depths (5-12 km) in the Sierra Nevada, California show similar structures to the shallower faults, with slip localized on a narrow (1-4 cm) surface.
3) Large offset faults have very similar microstructures to small offset faults. This shows that the deformation mechanisms that are active early in the faults history remain active as the fault accumulates offset. Fault cores and slip surfaces are very narrow at all scales of faults.
4) No wake of process zone fractures is preserved around the faults, showing that the majority of deformation is accumulated by repeated slip on the thin slip-surfaces. What tip-related process zone forms may lie within the fault zone itself, typically 10-20 m thick for the 10 km long faults in the Sierras, and up to 100-200 m thick for exhumed San Andreas faults.
5) Complex fault geometries are found at fault tips and segment boundaries. These may be sites of rupture arrest and/or jumping from one slip surface to another in a region of high fracture toughness. Linkage of the slip surfaces is the critical step in allowing the faults to grow through these zones.
6) The faults in this study nucleated on pre-existing cooling joints within a uniform granodiorite. Studies of faults exhumed from seismogenic depths in other lithologies are important to quantify the effect of lithology on fault zone structures and the complexity of terminations and segment boundaries.

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Discussion:

Catherine Homberg (Paris U.): Are the secondary faults compatible with the primary slip faults?

James Evans: We don't know. We see the through-going slip surface, but looking at these subsidiary faults we don't know how much rotation there has been in relation to the primary slip surface, because we don't know when these smaller faults formed.

Catherine Homberg: You may have an indication of that by deducing the stress state.

James Evans: We've done some simple things; at the Punchbowl fault, if you analyze the subsidiary faults, you actually get a left lateral strike-slip fault, for the stress regime adjacent to the Punchbowl Fault.

Kevin Furlong (Penn State): You saw extreme localization very early in the strain history of
the fault. Two questions: Do you see any variation with depth? And how much slip occurred by the time this extreme localization occurred?

James Evans: To answer the second question first: The amount of slip is tens of centimeters. And how deep? The slip surfaces seem to continue to some depth. The micromechanisms responsible for accommodating the slip may change, but we think that the notion of a broadening slip surface doesn't apply, at least to the faults that we've looked at.

Mark Zoback (Stanford U.): Can you help us with the geometric problem of accommodating tens of kilometers of slip in a very narrow zone? You're fine if you've got a perfectly planar surface.

James Evans: Well, there are many people working on this problem, but we think that the damage zone represents kinematic damage, so that the motion of asperities past each other is represented in the damage zone. Is slip accommodated there? No, the damage zone represents the secondary effects of the primary slip surface.

Roland Bürgmann (Berkeley): Can you say something about aseismic slip, and the magnitude of fluid pressures?

James Evans: I can say several things about both. Some of the faults have relatively high fluid pressures. In terms of seismic vs. aseismic processes, I wonder if the principal slip surface isn't the gun that's getting loaded. We see a lot of background seismicity in the damage zone,
which may serve to load the asperities on the principal slip surface.