Ductile and brittle deformation in a fault gouge zone, Jade Cove, Monterey County, California

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INTRODUCTION

Jade Cove occurs at the southern end of a 280 x 23 meter block of serpentinite surrounded by greywacke of the Franciscan complex. The southern end of the serpentinite block is defined by a brittle fault zone that contains serpentinite and greywacke gouge (Fig. 1). Rock friction experiments show two major modes of brittle deformation: 1) rate weakening behavior that leads to earthquakes (seismic), and 2) rate strengthening behavior that leads to stable (asiesmic) fault creep (e.g., Allen, 1968; Irwin et al. 1975; Reinen et al., 1991; Reinen et al. 1995). Reinen et al. (1995) show that serpentinite exhibits rate strengthening behavior at low slip velocities and both types of behavior occur at high slip velocities. In addition, at low slip velocities S-C fabrics were produced indicating that strain was distributed and at high slip velocities discrete shears were produced indicating that strain was localized. In this study, the fault zone at Jade Cove is examined to determine the natural deformation style of serpentine/talc rock and meta-greywacke and how the deformation behavior varies with scale.

BRITTLE DEFORMATION

The southern contact between serpentinite and greywacke at Jade Cove is defined by a 9 m by 8 m fault gouge zone that is bounded by serpentinite to the north and meta-greywacke to the south (Fig.1). The serpentinite gouge consists of a matrix of clay-sized serpentine and talc, and clasts of serpentinite. The grey, highly foliated fine-grained greywacke contains quartz, plagioclase, and potassium feldspar in a clay matrix. Below the fine-grained foliated greywacke is a small exposure of greywacke-derived gouge and cataclasite (Fig.1).

Localized Deformation. The most prominent feature in the outcrop is a large through-going Y-shear that defines the boundary between the massive/fractured serpentinite and the serpentinite gouge (Fig. 1). In addition, a R1 shear and associated small shear planes in an orientation consistent with P-shear orientation are present in the serpentinite gouge. The Y, R1, and P shears are all lined by talc. Less defined, but still visible are tensile fracture traces, also lined with talc. The fractured serpentinite unit is highly brecciated along the Y-shear boundary with large broken grains of serpentinite material spread out in the orientation of the bounding shear.

In thin section, broken grains and brecciation characterize the serpentinite gouge. In Figure 2 the cataclastic texture is clearly evident, and is defined by unoriented, fractured grains of serpentine minerals. Note that localized fracturing is occurring within grains as well as along grain boundaries. The meta-greywacke gouge also has a cataclastic texture with extensive fracturing of individual grains and no mineral preferred orientation (Fig. 3).

Distributed Deformation. There is some evidence of strain accommodation by distributed processes in the outcrop. An 8 cm by 1 m area located below the Y-shear in the serpentinite gouge exhibits two well-defined C-shears and several poorly developed S shears all lined by talc (Fig. 4). Located between the talc-lined S foliations are areas of massive serpentinite gouge.

PLASTIC DEFORMATION

The talc layer along the prominent Y-shear that defines the boundary of the serpentinite gouge varies in thickness from 0-2 cm. Talc within the layer has a well-developed S-C fabric with the C surfaces parallel to the Y-shear boundary (Fig. 5). The orientation of the S surfaces suggest dextral (top to the South) shear along the Y-shear. The S foliation is defined by the shape preferred orientation of talc.

DISCUSSION AND CONCLUSIONS

The fault zone at Jade Cove contains evidence for both localized and distributed deformation. In serpentinite and meta-greywacke, the majority of the features observed at the outcrop scale were the result of brittle deformation. The presence of a boundary parallel fault (Y-shear), R1 shears, tensile fractures, possible P shears and extensive brecciation and fracturing of the serpentinite and adjacent greywacke all indicate localized strain (Figs 1-3). Distributed deformation is evident in S-C fabric located in the serpentinite gouge 4-6 cm below the Y-shear (Fig.

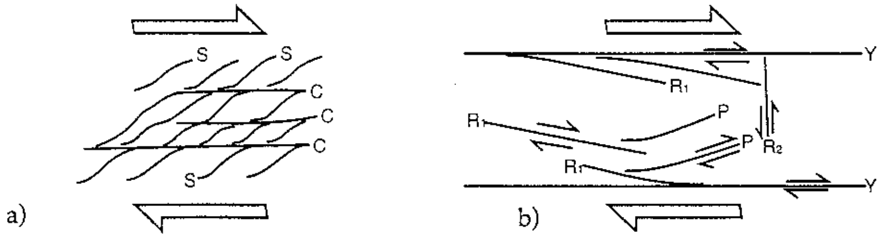

Figure 1: a) General form of s-c fabric (associated with ductile deformation). b) General form of and sense of movement along Reidel, p-, and y-shears (associated with brittle deformation). Large arrows indicate sense of shear for both diagrams. (Modified after Passchier and Trouw, 1996).

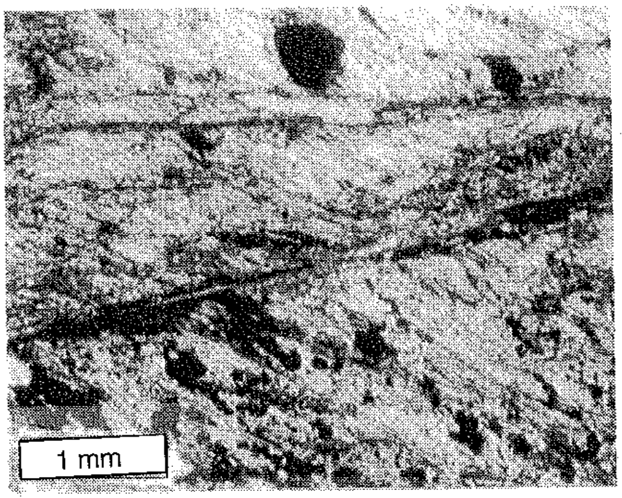

Figure 2: Photomicrograph of R_1 shear (linear feature running down to the left) cutting through s-c fabric. South is to the left; sense of shear is top to the south.

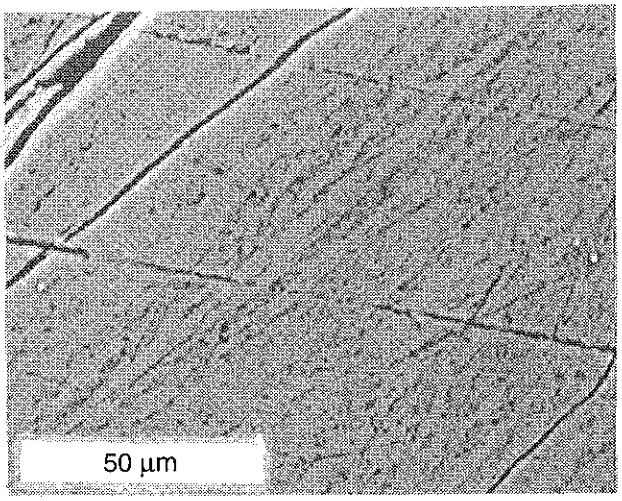

Figure 3: SEM image of serpentinite in an s-c fabric. Two s-surfaces are visible in the upper left corner. The straight lines running down to the right are scratches.

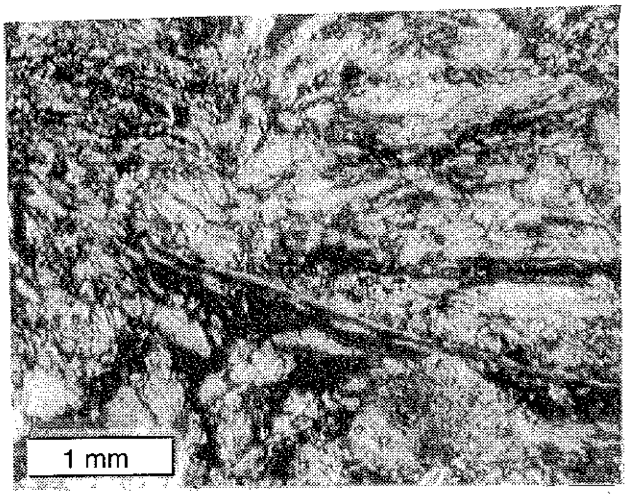

Figure 4: Photomicrograph of R1 shear curving into a y-plane in a sample from the highly deformed layer. The darker color of the R1 shear is from clay minerals. Notice the lack of s-c fabric or consistent grain orientation. South is to the right; sense of shear is top to the south.

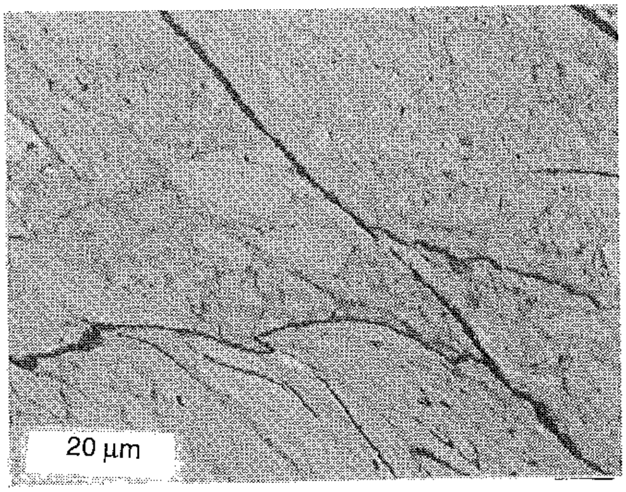

Figure 5: SEM image of sample from the highly deformed layer. Notice the lack of a consistent fabric. South is to the right.

4). In thin-section and SEM analysis the serpentinite exhibits broken mineral grains, cataclastic textures, microfaulting and random fabric all characteristic of localized deformation. However, the presence of an S-C fabric in the talc layer along the serpentinite gouge bounding Y-shear suggests that some of the strain in the fault zone was accommodated by the crystallization of the talc (Fig 5). Therefore, plastic deformation mechanisms were also active during deformation in the fault zone.

The S-C fabric that is located in the gouge (Fig. 4) has talc along the S and C surfaces, but has unoriented serpentinite gouge between the S foliations. This suggests that the presence (crystallization?) of talc influences the deformation style, by promoting distributed deformation in the serpentinite gouge. Alternatively, distributed deformation fabrics like the S-C fabric in the serpentinite might allow easier access for fluids into the fault zone, thus promoting the growth of talc in these areas.

Experimental data indicate that localized and distributed deformation can occur in serpentinites at high slip velocities (e.g. Reinen et al., 1995). This suggests that high slip velocities might be responsible for some of the fabrics in the Jade Cove fault zone. However, the growth of talc during deformation in the fault zone might also control the observed deformation style.

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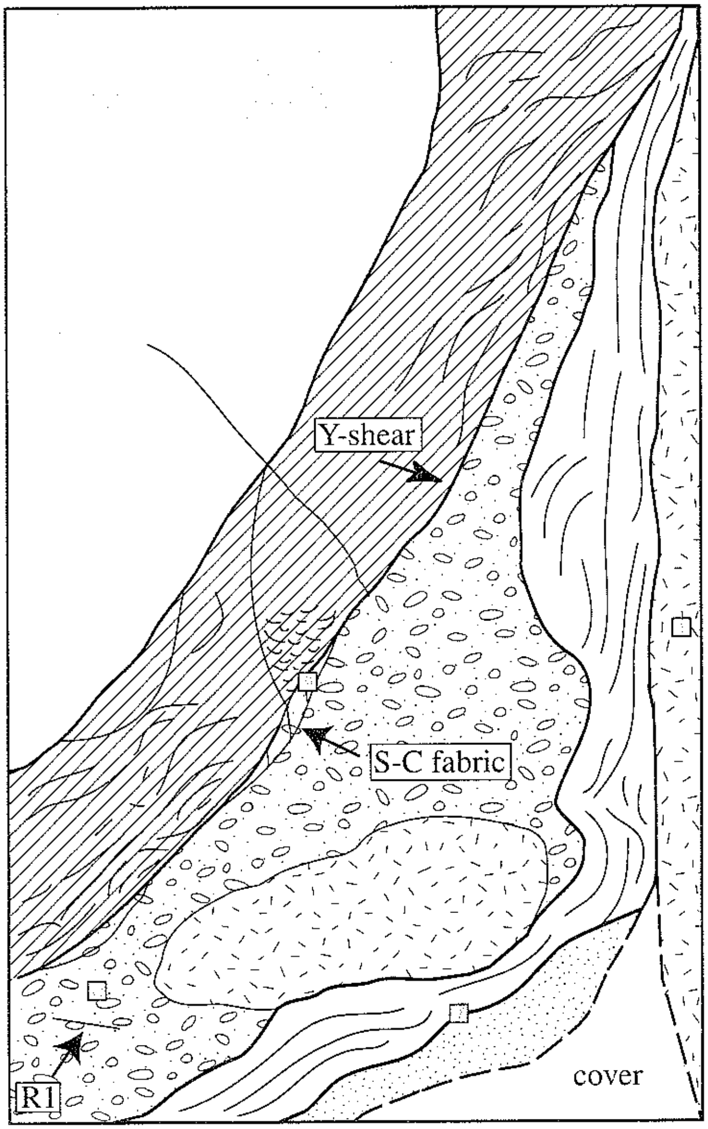

Figure 1. Map of gouge zone at Jade Cove. The massive serpentinite is the dominant rock type at Jade Cove. The fractured serpentinite occurs only in small bands bounding the gouge zone. Serpentinite gouge is loosely consolidated serpentine (lizardite/antigorite) with talc veins and phacoid blocks. Foliated greywacke cataclasite is fine-grained, highly foliated rock. Foliated greywacke is fine to medium grained with extensive quartz veining. Greywacke gouge is moderately consolidated, with pebbles interspersed throughout. The S-C fabric noted in the figure is shown in in detail in Fig. 4.

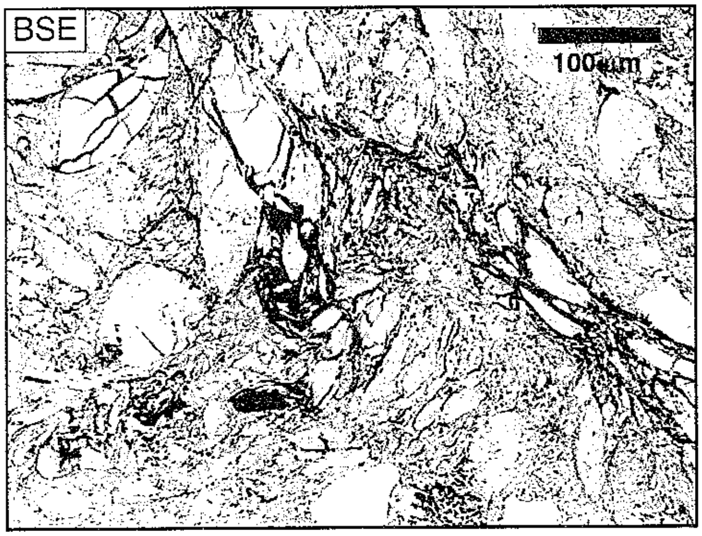

Figure 2. Backscattered electron image of brittle behavior in the serpentinite gouge. Note the occurance of localized fracturing within and between grains. Material consists of lizardite/antigorite.

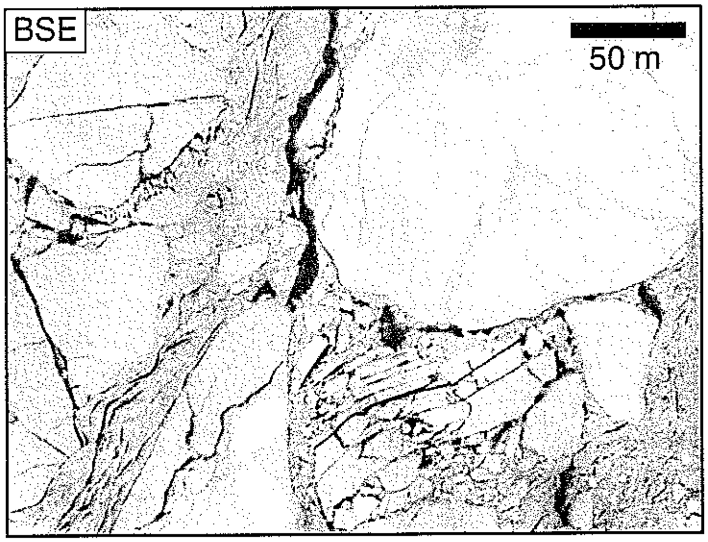

Figure 3. Backscattered electron image of brittle behavior in greywacke gouge. Note the highly fractured grains and lack of a dominant foliation. Material is primarily quartz, potassium feldspar, and clay.

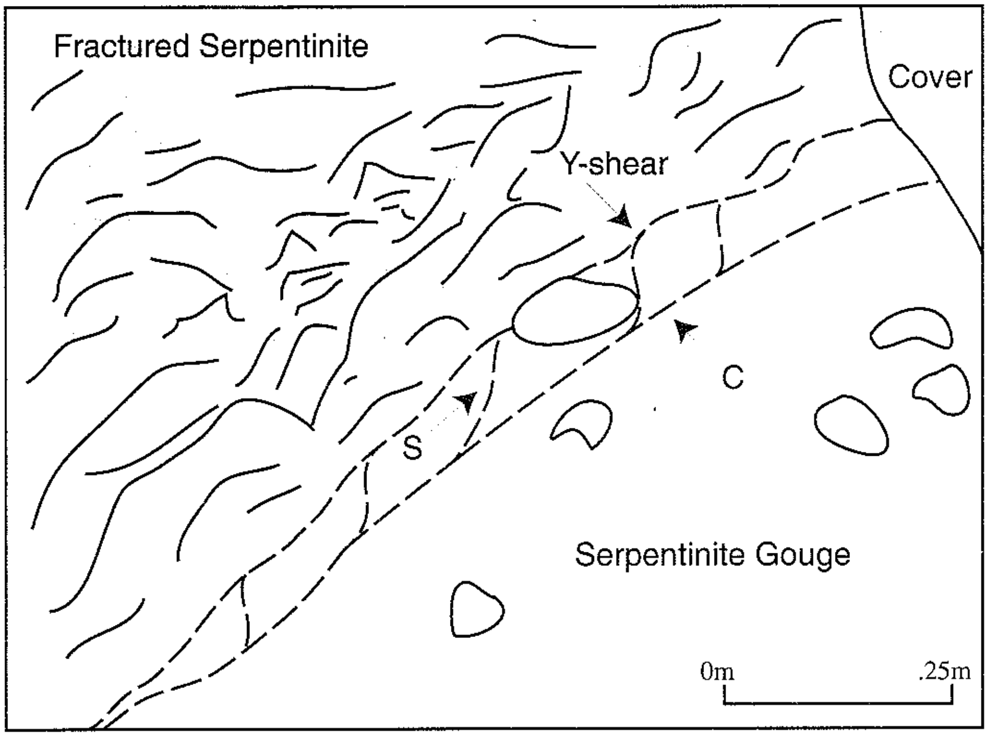

Figure 4. Line drawing of distributed deformation on the outcrop scale. Arrows mark the shear boundary (C) and schistocity (S) within the fabric. Dotted lines indicate all features that are lined with talc.

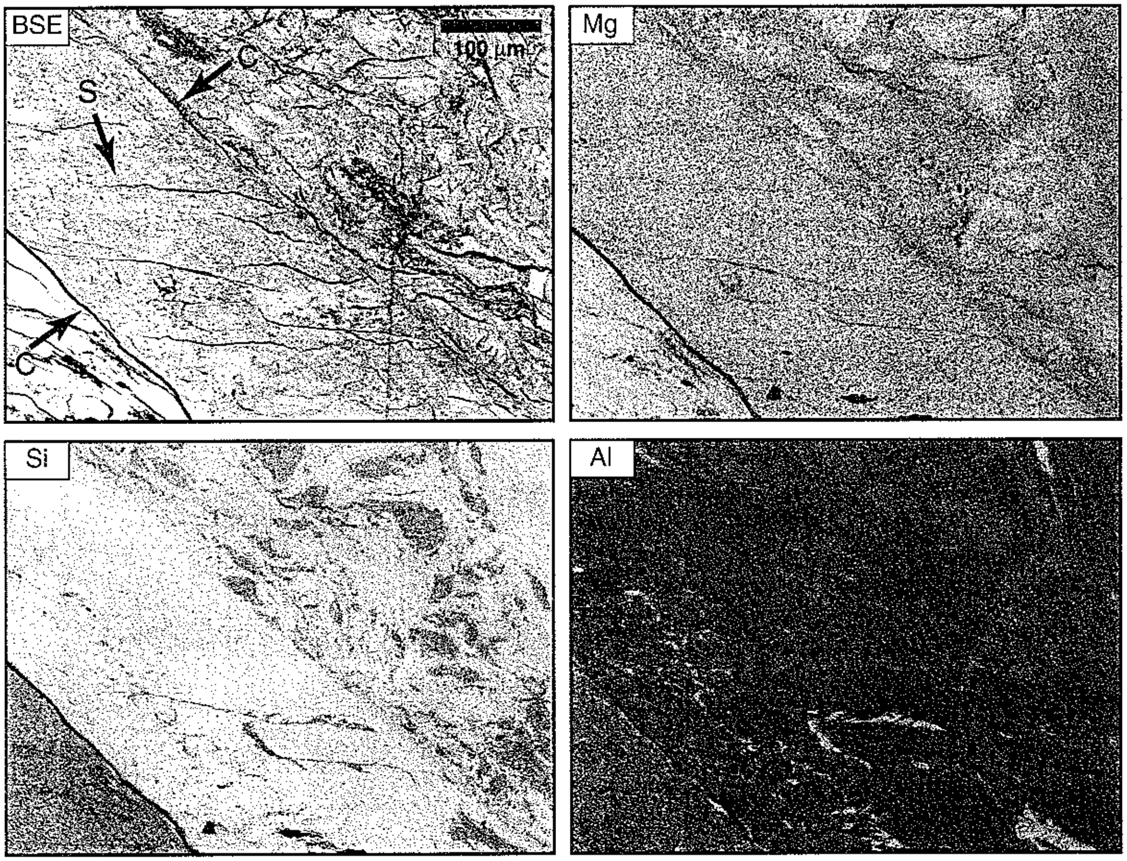

Figure 5. Backscattered electron image and x-ray maps of plastic deformation in the serpentinite gouge. Bright areas have higher concentrations of the elements in the x-ray maps than the dark areas. Arrows indicate S and C foliations. Light material in lower left of BSE is lizardite or antigorite. The foliated, Si-rich material is talc, and the cataclasite in upper right is lizardite/antigorite + talc.

A macro- and micro- structural analysis to determine the deformation style of serpentinite gouge, Jade Cove, Monterey County, California

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ABSTRACT

A serpentinite fault zone, in proximity to the Sur-Nacimiento Fault of California, was studied and its shear structures documented. Field evidence supports experiments that show serpentinite shifts from rate strengthening behavior to rate weakening behavior when reaching a critical loading velocity. These two modes of mechanical behavior are characterized by the presence of both brittle and ductile structures in the zone. Macrostructures at the outcrops scale, as well as microstructures and fabrics within the gouge, provide evidence of both seismic and aseismic episodes. Structurally, the zone displays both localized and distributed deformation. Riedel (R1) shears that bend into parallelism with Y shears, overall clast brecciation, and boundary-local serpentinite fractures, suggest local deformation induced by seismic events. However, microstructures such as lattice-preferred orientation, weak s-c fabrics, and an overall flow-like gouge fabric, suggest that portions of the gouge zone distributed deformation aseismically as a result of typical plate rates. In support of experiments previously performed, this study provides field evidence that the abundance of serpentinite within fault zones may allow for two styles of deformation. Therefore, it is the properties of the serpentinite and the subsequent loading velocity in which it was subjected, not necessarily pressure/temperature conditions alone, which cause evidence of both brittle and ductile regimes to coexist.

BACKGROUND

Serpentinite is a common rock within faults and major shear zones (Christensen, 1972; Allen, 1968). Experiments conducted by Reinen et al. (1991), suggest that serpentinite exhibits two modes of mechanical behavior as a function of loading velocity (Fig. 1). Velocities equivalent to average plate rates result in experimental rate strengthening behavior. Such behavior is characterized by distributed deformation analogous to ductile regimes. Conversely, faster loading velocities result in rate weakening behavior, analogous to brittle regimes. Strain characteristics of serpentinite gouge zones should therefore be different than most common quartzo-feldspathic rocks that exhibit only rate weakening tendencies (Tullis and Weeks, 1986; Blanpied, 1987). It is this rate strengthening characteristic of serpentinite which may be responsible for the reduction of seismic activity along these "creeping sections" of the San Andreas, as well as other zones of reduced seismic activity.

TABLE 1. BRITTLE AND DUCTILE CHARACTERISTICS

Deformational regime:	**Brittle**	**Ductile**
Constitutive behavior:	rate weakening	rate strengthening
Types of Structures:	Riedel (R, R1, Y) shears	S-C fabrics
	broken grains	optical continuity
	cataclasite	augen structures
Overall deformation:	localized	distributed
Geologic behavior:	seismic	aseismic
Earthquake risk:	yes	no

(Adapted from Reinen et al., 1991; Chester et al., 1993; Passchier and Trouw, 1996)