Microstructures as Indicators of Larger Scale Deformational Patterns in Serpentinites from Sand Dollar Beach, Monterey County, California

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INTRODUCTION

Lab experiments have shown that serpentinite shows two rate-dependent modes of deformation (Reinen et al., 1994). The first mode is a ductile, distributed deformation not confined to an identifiable surface or (generally) planar zone. It is associated with aseismic creep and corresponds to low stress-loading velocities. The other mode is a brittle deformation in which there are in localized zones or even single surfaces along which the deformation is accommodated. It is associated with seismic slip and corresponds to high stress-loading velocities.

Microstructural examination of the experimentally deformed serpentinites reveals that distinct structural patterns form under each of the deformational modes. Ductile deformation results in s-c fabric, while brittle deformation results in Reidel (R_1 and R_2) shears, p-shears, and y-shears (Fig. 1) (Reinen and Tullis, 1995).

While other research has shown that these fabrics also exist in naturally deformed serpentinites (Hoogerduijn Strating and Vissers, 1994 and Norrell, 1989), the larger implications of a microstructural distinction based on mode of deformation have not been sufficiently discussed.

The focus of this study is to address the question of whether or not the experimentally observed microstructural distinction between brittlely and ductilely deformed serpentinites provides any useful or dependable insight into the larger scale picture of deformation in naturally deformed serpentinites as observed at Sand Dollar Beach, Monterey County, California. In other words, if you see a particular set of microstructures in a rock, can they be used reliably to tell something about the larger picture of deformation within the rock?

GEOLOGIC SETTING

The serpentinite considered in this study is found in an outcrop on the northern end of Sand Dollar Beach, near Big Sur California. This outcrop is part of an exotic serpentinite block, bounded by graywacke, within the Franciscan complex. It is most likely a part of the Coast Range Ophiolite. This particular outcrop is a serpentinized peridotite and thus is from the ultramafic (mantle) portion of the ophiolite. The study area is also part of the Sur-Nacimiento fault zone, a proto-San Andreas fault zone which marked the boundary of the North American continent during the late Cretaceous and early Tertiary (Page, 1970).

METHODS

Mapping: A section 150 meters long and 4 meters high of the outcrop was mapped with Heidi Reeg. Two approximately 1 meter square sections were mapped on a 4:1 scale. Also, orientations of structures were measured.

Sampling: Sites representative of deformational styles and structures of the outcrop as a whole were identified within and nearby the squares, coated with epoxy, oriented, and removed from the outcrop. The samples were heated and coated with additional epoxy. Chips were cut and sent away for thin sectioning so that thin sections would be cut parallel to the direction of shear and perpendicular to the plane of flattening.

Analysis: Using a petrographic microscope, the type, size, and density of microstructures, grain size, grain orientation, composition, and sense of movement seen in each thin section were noted and recorded. With much help from Krassimir N. Bozhilov, two thin sections were polished, carbon coated, and examined under an SEM both for structures and composition. XRD analysis was also done on a number of samples which had been disaggregated using a mortar and pestle, and sieved through a 200 micron mesh sieve, and run through an XRD.

OBSERVATIONS

The overall picture of deformation within this exposure of serpentinite is of distributed, ductile deformation (seen as the preferential orientation of phacoids and a primarily compositionally defined s-c fabric), overprinted with some features of localized, brittle deformation (including large scale Reidel and y-shears, a few fault planes, and in one section, a continuous, fairly planar, well-defined 30 cm thick layer which is very highly deformed).

Small section scale observations: In both small areas, the overall picture is of ductile, distributed deformation, best exemplified by the presence of s-c fabric, which indicates a general top-to-the-south sense of

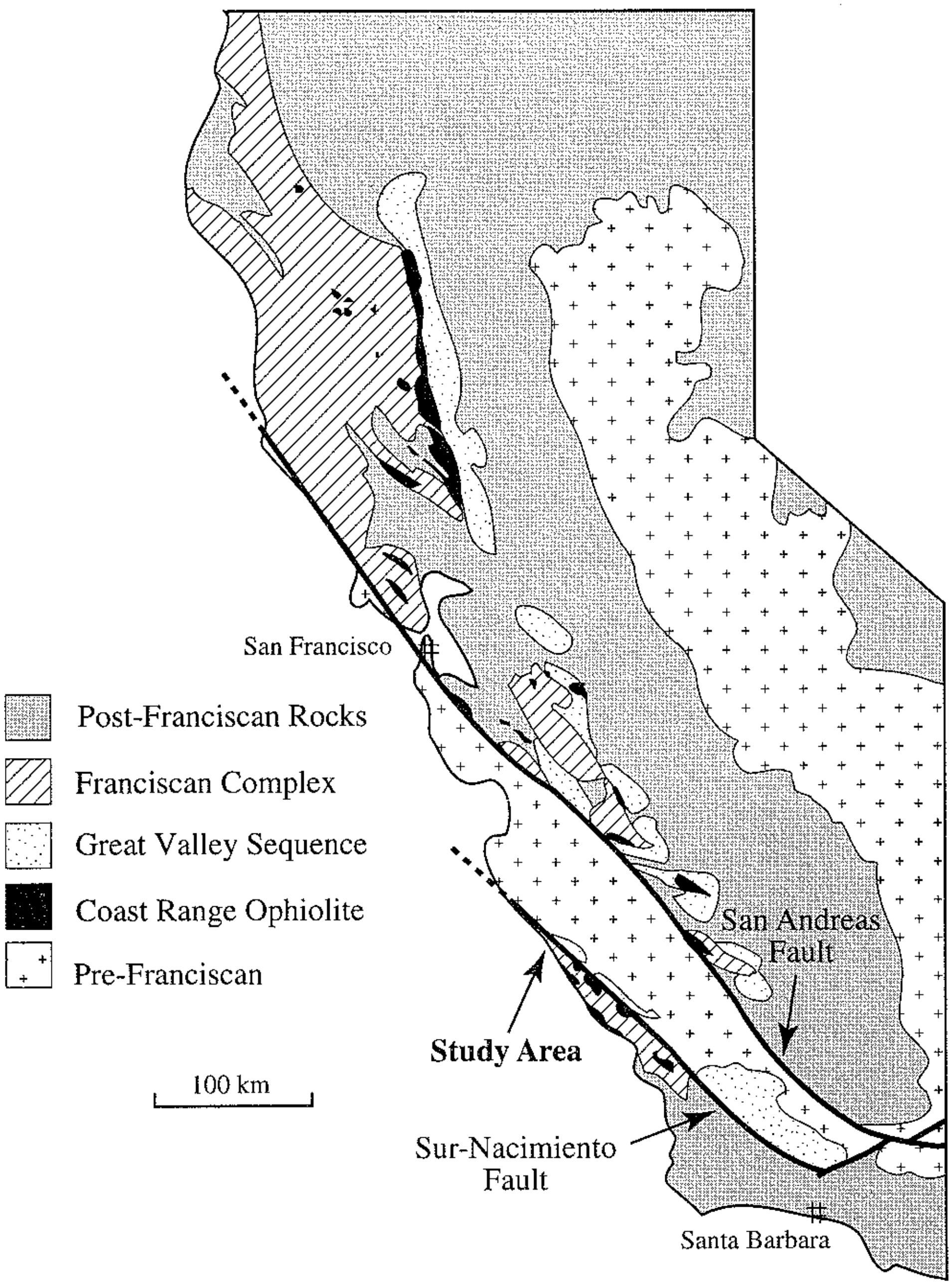

Figure 3. Tectonic map of central California, showing the location of our study area. (Modified by R. Cahill after Hopson et al., 1981)

shear. The s-c fabric is defined both compositionally within the serpentine and by preferential orientation of one to five centimeter long phacoid pieces, which are not internally distorted by the fabric. There is late-forming serpentine between phacoids and within cracks of the phacoids, including a few (presumably antigorite) beards, one of which has been cut and slightly offset by a small fault surface.

There are many linear (assumed to be planar in three dimensions) features running through the sections. Some are less through-going, more local structures (c-surfaces). Other features are more continuous, through-going, crosscutting, and continue well beyond the arbitrary confines of the square, and some also have cataclastic material along them. These features are R_1, p, and y-shears.

Area 1 contains a part of the highly deformed layer, which seems very highly sheared, in that the foliation is very dense and there are no phacoid chunks visible to unmagnified inspection. The foliation shows a number of apparently random, confused, and distorted orientations. Cutting through this fabric are R_1 and p-shears.

Above the highly deformed layer is a thin (less than 1/2 cm) layer of a white material which is somewhat less weathered and sticks out slightly. The layer has a sort of s-foliation which is more apparent in weathered relief, and one apparent R_1 shear. There are northeast/southwest running striations on the underside of this layer.

Microscale and compositional observations: In thin section, many samples exhibit well-formed s-c fabric, defined by a combination of composition (especially in the lens-shaped zoning of oxides) and grain orientation, indicating a top-to-the-south sense of shear (Fig. 2). The rock has split along many of the s and c surfaces (perhaps due to reduced pressure after formation), and calcite veins have formed in a few of these splits. The vast majority of grains are elongate, although in several places interlocking texture and smaller, less elongate grains lacking a preferred orientation can be seen, and some ribbon serpentine has formed. The samples are composed of serpentinite with a fair amount of opaque oxides (primarily magnetite and chromite). SEM imaging of these sections shows a fabric with the same orientation as the s-surfaces (Fig. 3).

Most samples with ductile structures showed the ductile structures being overprinted and cut cleanly through by R_1, y, and p-shears associated with brittle deformation (Fig. 2). Brittle structures were never observed being deformed by ductile structures, but in some places brittle structures cut through and even offset other brittle structures. Some cataclasite-filled brittle features show late-forming serpentine in cracks within the cataclasite.

The highly deformed layer in Area 1 is slightly different. The overall grain size in these sections is somewhat smaller than the grain size in other samples, and while many grains are elongate, they lack the same sense of a consistent preferred orientation. In some places, pieces of a disturbed or distorted s-c fabric can be seen. Many R_1 shears, y-shears, and p-shears are visible (Fig. 4). The composition of these sections is also serpentinite with some oxides, but with a larger amount of clay minerals (especially along R_1 and y- shears). SEM images of sample I are consistent with this idea of disturbed s-c fabric and more random overall fabric (Fig. 5). A sense of shear was harder to determine from these sections, but the general sense is still top-to-the-south.

The most intriguing samples are ones taken from the thin layer above the highly deformed layer in Area 1. Thin sections of this band show the s-foliation apparent at the hand-sample scale even more clearly. SEM images of the band also show a beautiful s-c fabric. Compositional analysis revealed that this layer is made of a mix of clay minerals, mixed on such a fine scale that exact composition could not be determined even with the SEM.

DISCUSSION

Samples taken from areas with macroscale features indicating distributed, ductile deformation being overprinted and cut through by structures indicating brittle deformation exhibit microstructures associated with ductile deformation being cut through by brittlely associated microstructures as well. Samples taken from the highly deformed layer in Area 1 exhibit undistorted macro- and microstructures associated with brittle deformation, but only variably oriented and distorted or disturbed structures associated with ductile deformation.

Samples from the thin layer on top of the highly deformed layer show s foliation in thin section, and s-c fabric on the SEM scale. Such microstructures are associated with ductile deformation in serpentinite. However this band is not serpentinite, but an extremely fine mixture of various clay minerals. Perhaps as a result of this layer being so fine-grained, it might have behaved plastically even under very high loading velocities.

Thus, serpentinites from this outcrop show a consistent pattern of structures associated with ductile deformation (mostly s-c fabric or other foliation) being overprinted by and cut cleanly through by structures associated with brittle deformation (R_1 shears, p, and y-planes). This pattern is consistent on three levels: whole outcrop scale (10s of meters), small section scale (10s of cm), and thin section scale. A top-to-the-south sense of shear is also consistent between brittle and ductile structures and on all scales.

Because the s-c fabric is primarily compositionally defined, it was probably created when a serpentinization event happened while the outcrop was undergoing strain. It appears that after this s-c fabric formed there was a reduction in pressure, as some of the s and c-surfaces appear to have popped open. Also, the s-c fabric formation appears to have been followed by multiple episodes of brittle deformation and additional serpentine recrystalization. The brittle deformation followed the ductile because there are brittle features cutting through ductile features cleanly and continuously, and distorting ductile features, but brittle features are never observed being incorporated into or deformed by ductile features. We can tell there were multiple episodes of brittle deformation because brittle features offset other brittle features. Additional serpentine recrystalization can be observed in ribbon-texture serpentine, serpentine filling cracks in brittle features, and in beards forming on phacoids. These recrystalizations were intermixed in time with the brittle deformational events because we can see both late serpentine formation within some brittle features and some brittle features cutting through and even offsetting recrystalized serpentine, especially the beards.

Although compositional variations (both in terms of impurities and polymorphs of serpentine) have been invoked in laboratory research as a determining factor of deformational mode, this does not seem to be the main factor here. Petrographic, XRD, and SEM analysis showed no significant variations in composition While none of these methods were refined or accurate enough to make positive identification of serpentine polymorphs, it could still be asserted that composition was not the primary or even a major control on where a particular type of deformation occurred as both brittle and ductile features were seen affecting the exact same samples.

Since composition does not appear to be the main factor here, it might be speculated that either loading velocity or P-T conditions were more responsible for the determination of deformational mode. While it is possible that there was originally a slower loading velocity followed by exclusively faster loading velocities, it seems more likely that P-T condition changes were responsible for determining the deformational mode.

This outcrop is probably part of an ophiolite, and was part of a subduction zone environment. If this outcrop were first involved in subduction, and then brought up onto the continental crust as part of an ophiolite, it could very well have first experienced higher metamorphic conditions (conducive to ductile deformation), followed by consistently lower metamorphic conditions (conducive to brittle deformation). This would lead naturally to the pattern of ductile deformation overprinted with brittle deformation.

CONCLUSIONS

This outcrop represents a shear zone (a localized high strain zone) with top-to-the-southeast sense of shear that probably formed during the subduction and subsequent uplift and emplacement of an ophiolite complex. It exhibits evidence of both ductile and brittle deformation at the scale of the outcrop, smaller sections of the outcrop, thin sections, and SEM.

The neat correspondence between deformational mode and microstructures observed in the laboratory cannot be made in this outcrop because features associated with both brittle and ductile deformation occur in the same samples, and it is impossible to know for sure the mode of deformation actually experienced by any particular part of the serpentinite. The largest problem is the outcrop appears to have undergone multiple deformational episodes. The same areas seem to have undergone both ductile and brittle deformation and thus it is reasonable that the same sample would show structures on all scales reflecting both styles of deformation.

However, the overwhelming majority microstructures seem consistent with macro-scale structures in presence, order of occurrence, and sense of shear. On all levels we see ductile features overprinted by brittle features, never brittle incorporated into ductile. All of these things indicate that microstructures associated with brittle and ductile deformation are probably good indicators of macroscale deformation of the same nature, and can give us useful insight into the larger scale deformational style and history of an outcrop.

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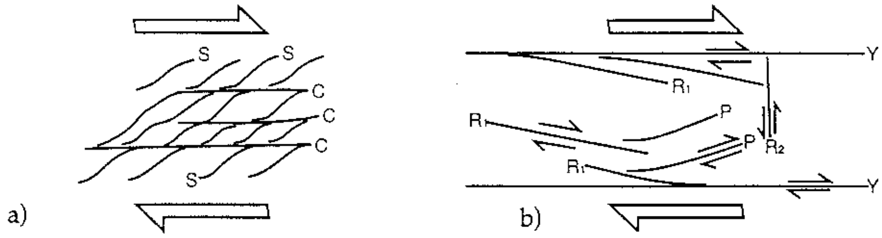

Figure 1: a) General form of s-c fabric (associated with ductile deformation). b) General form of and sense of movement along Reidel, p-, and y-shears (associated with brittle deformation). Large arrows indicate sense of shear for both diagrams. (Modified after Passchier and Trouw, 1996).

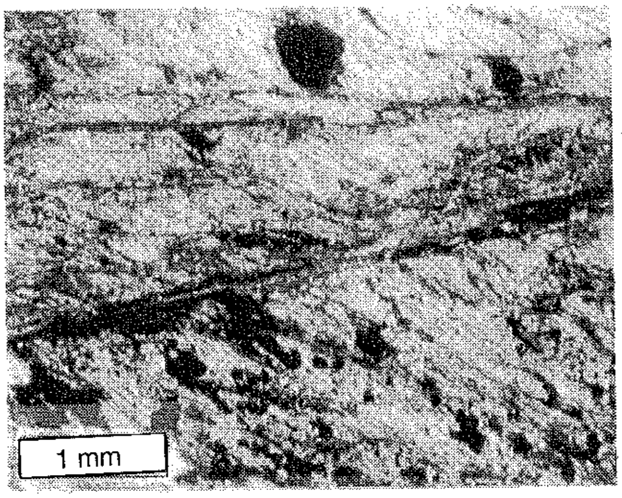

Figure 2: Photomicrograph of R_1 shear (linear feature running down to the left) cutting through s-c fabric. South is to the left; sense of shear is top to the south.

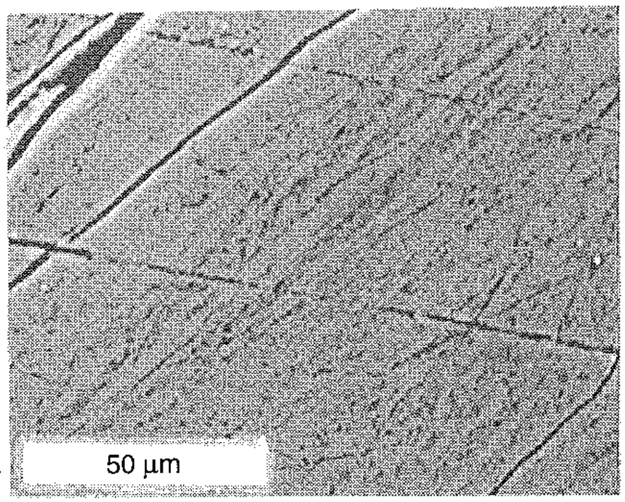

Figure 3: SEM image of serpentinite in an s-c fabric. Two s-surfaces are visible in the upper left corner. The straight lines running down to the right are scratches.

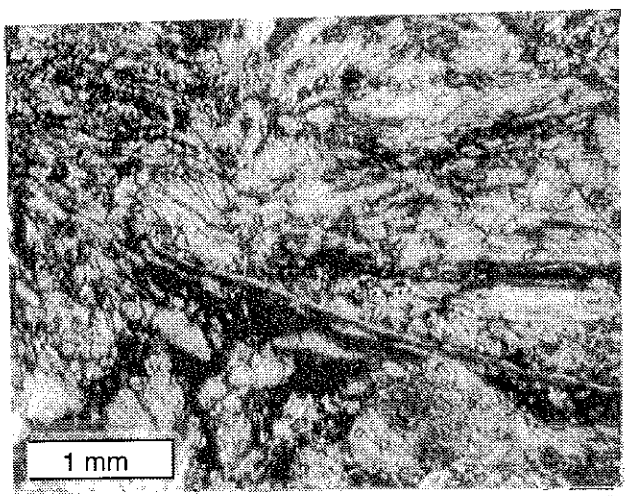

Figure 4: Photomicrograph of R1 shear curving into a y-plane in a sample from the highly deformed layer. The darker color of the R1 shear is from clay minerals. Notice the lack of s-c fabric or consistent grain orientation. South is to the right; sense of shear is top to the south.

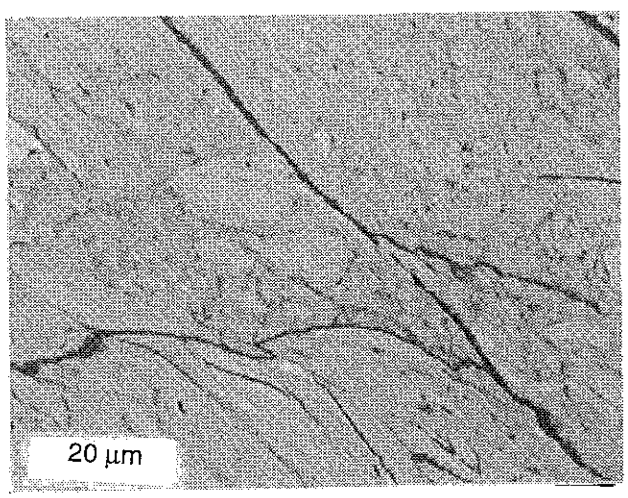

Figure 5: SEM image of sample from the highly deformed layer. Notice the lack of a consistent fabric. South is to the right.

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.