Structural variations in deformed serpentinite, Monterey County, CA

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INTRODUCTION

The San Andreas fault exhibits two distinct types of movement in different places along its trace. The areas near San Francisco and Los Angeles have experienced large earthquakes in recent time: 1906 and 1857 respectively (Allen, 1981). However, other than these large events, the San Andreas fault is locked in these areas and experiences only occasional small earthquakes (Irwin & Barnes, 1975). The central section of the fault, between Cholame and San Juan Baptista (Irwin & Barnes, 1975), exhibits stable aseismic fault creep at a high and relatively constant rate, up to 33mm/yr (Allen, 1981). These portions of the fault also frequently experience earthquakes of smaller magnitude and some moderately sized earthquakes (Wallace, 1970). There are hypotheses as to the cause of the variance in slip behavior along the San Andreas fault. One popular hypothesis attributes the stable creep motion of the central portion of the San Andreas fault to the presence of serpentinite (Irwin & Barnes, 1975; Allen, 1968).

Serpentinite is found on many faults and may be responsible for stable fault creep (Reinen & Tullis, 1995; Dengo & Logan, 1977; Moore & Lockner, 1997). Byerlee and Brace (1968) suggested that serpentinite may act as a lubricant along fault traces, allowing constant motion rather than sticking followed by large seismic events. However, laboratory experiments have shown that the coefficient of friction of serpentinite is too high for the rock to be able to lubricate fault blocks (Dengo & Logan, 1981). Thus, further experimentation was conducted to test alternate hypotheses.

It has been determined in friction experiments that serpentinite responds to changes in slip velocities in two distinctly different styles: a rate-weakening style at higher velocities, and a rate-strengthening style at lower velocities (Reinen et. al., 1992). This implies that at the low velocities of plate boundaries, only stable fault creep should occur (Reinen et. al., 1990), as long as the slip along a fault is accommodated by frictional sliding of serpentinite. This will occur because resistance to slip increases with velocity, thus inhibiting escalating rates of sliding. However, if the fault begins moving at a higher rate for any reason, the serpentinite will allow the movement to accelerate, due to its rate weakening nature at faster velocities.

The two styles of deformation have been observed in experimental studies. Microstructures vary between the areas deformed under high slip velocities and those deformed under lower slip velocities. In the faster velocity mode, the serpentinite showed more localized deformation structures such as Riedel shears (Reinen & Tullis, 1995). In contrast, structures representing distributed deformation, such as S-C foliation, were produced in the slower velocity mode. Because these variances exist in the laboratory, it is important to determine whether they occur in nature as well and can give insight into the paleoseismicity of the fault zone.

The serpentinite outcrop we studied is located on Sand Dollar Beach in Monterey County, California. The rocks originated as mantle peridotites that are now a part of the Coast Range Ophiolite. This ophiolite was formed between 153-165 Mya in the Mid-Jurassic (Hopson et al., 1981). The initial serpentinization of the peridotite occurred approximately 3-5 km beneath the ocean floor in the late Jurassic Period. During the late Cretaceous, the Great Valley Sequence, consisting of sandstones, was deposited on top of the Coast Range Ophiolite (Bailey et al., 1970). At the same time, the Franciscan complex of sandstone, siltstone, greenstone and chert was being deposited further offshore. The ophiolite was in the forearc basin of an ancient subduction zone and, thus, was in the hanging wall of the subduction complex. The Franciscan complex was thrust beneath and now underlies the Coast Range Ophiolite (Dickinson, 1983). Its jumbled, metamorphosed nature suggests that it was part of the subduction complex that was accreted onto the underside of the ophiolite during subduction (Jayko et. al., 1986). According to Bogdanov and Dobretsov (1987), the last episode of thrusting along this boundary occurred in the late Cretaceous/early Paleocene Epoch (60-65 mya).

Serpentine is found in the lowest of the layers at the base of the ophiolite (Hopson et. al., 1981). Page (1972) sited evidence of this from the subduction complex near San Luis Obispo, 100 km south of the field area. Thus, it is possible that large pieces of serpentinite were broken off the hanging wall during subduction and incorporated into the underthrusting rock body. The ultramafic complex is also exposed in a strip along the south-west margin of the Franciscan melange (Hart, 1976). The serpentinite in these outcrops ranges in texture from massive to sheared and occurs in thin bands along faults.

The field area is located in the Sur-Nacimiento Fault zone which consists of north-west trending faults extending 280 km south-east from Monterey (Hart, 1969). Page (1970) suggests that the fault zone may have been the former continental margin, as it separates the Salinian Block from terrane covering eugeoclinal deposits. The edge of the oceanic crust remnant is less than 4 km from the Sur-Nacimiento Fault zone (Page, 1972). It has been hypothesized that the Sur-Nacimiento Fault is an ancient trace of the San Andreas Fault (Page, 1981). There is evidence that the present San Andreas Fault had a predecessor before the Eocene. Thus, the proto San Andreas Fault could conceivably have been located along the present day Sur-Nacimiento Fault.

METHODS

Fieldwork. I selected an area on Sand Dollar Beach for field work based on the availability of freshly exposed serpentinite outcrops and the variety of structural features showing both localized and distributed deformation. The large outcrop is a segment approximately 310 meters long. I chose two smaller areas (50*70cm and 61*63cm) within the larger outcrop to examine in detail. I took measurements of the orientations of foliation, veins, faults and shear sense indicators, such as elongate phacoids, using a Brunton compass. I recorded deformation styles, sequence of events indicators, and evidence of different serpentinization episodes. I also chose areas to sample both for X-ray defractometry and thin section analyses. We removed the samples using epoxy and a portable rock saw.

Labwork: I examined thin sections from the area to determine grain size, shape, interference colors, styles of deformation present, shear sense indicators and order of deformation events, in addition to mineral identification. I ran samples from various areas through the X-ray defractometer to determine dominant mineral compositions. In addition to XRD analyses, I examined polished thin sections using a scanning electron microscope.

I also transferred maps sketched in the field to computer files in Adobe Illustrator and constructed both a map of the whole outcrop and maps of the smaller sites.

FIELD OBSERVATIONS

I observed both distributed and localized deformation features in the outcrop on Sand Dollar Beach. Planar features, such as veins, fractures and faults, were visible on the mesoscale and in handsample. I also saw large to small phacoids, massive pieces of the protolith, interspersed throughout the outcrop. In my field area, there were three visibly distinguishable styles of deformation. First, areas where less deformation had occurred contained an abundance of large, slightly elongate phacoids with occasional recrystallization beards growing parallel to the direction of elongation. The second type of area was characterized by evidence of concentrated deformation, namely fractures and cataclasite-filled faults. Distributed deformation in the form elongation of grains and S-C foliation characterized the third type of area.

The types of distributed deformation I observed in the area are S-C foliation, recrystallized serpentine beards and zones of elongate phacoids with recrystallized beards around them. The foliation in general was dipping NE.

I observed more localized deformation in the form of splitting phacoids, Riedel shears in the orientation of Y and R1 shears, and cataclasite-filled faults. Within the deformation bands the cataclasite was nearly white with occasional black crystals.

LABORATORY ANALYSES

Thin sections and x-ray defractometry analyses show that the rocks in my study area are predominantly serpentine, with minor amounts of brucite, spinel and magnetite. I was not able to distinguish between the different polytypes of serpentine.

I examined the samples in the thin section and discovered a variety of microstructures. I observed both localized and distributed deformation features such as S-C foliation (fig. 1), cataclasite fault gouge, fractured ribbon texture grains, Riedel shears and episodic antitaxial vein growth. There is evidence of the relative timing of different deformation styles in thin section. Riedel shears cut across and displace S-C foliation. Calcite veins are often found alongside the R1 and Y shears with the same orientation. However, I also discovered calcite veins which had the same orientation as the S foliation planes. A zone of localized deformation on the mesoscale, approximately 8 cm wide, is highly foliated in thin section, indicating that within this zone of localized deformation later distributed deformation has occurred.

The scanning electron microscopy analyses indicate that localized and distributed deformation features are present at scales smaller than thin section. I observed both cataclasite fault gouge (fig. 2) and S-C foliation.

DISCUSSION

In the outcrop on Sand Dollar Beach, the serpentinite shows both localized and distributed deformation features which I attribute to brittle and ductile deformation mechanisms respectively. I consider the more distributed deformation styles to be a result of the rate-strengthening behavior of serpentinite. The rock behaved in a ductile manner in response to applied stresses. As the strain began to be propogated along a single plane or surface in the serpentinite, that particular area of the rock became stronger and deformation ceased. The strain needed to be accommodated in some manner and, thus, was transferred to a new portion of the rock. This new portion became stronger with the onset of movement, and the strain was transferred to yet another site in the serpentinite. In this fashion, the strain became more or less evenly distributed throughout the areas showing ductile deformation.

In areas where brittle structures dominate the deformation style, the serpentinite must have shown rate-weakening behavior. The strain was accommodated along a single plane or shear zone. As more stress was applied, the already deformed serpentinite became weaker and weaker and continued to deform along the existing shears and faults.

The structures I observed on the mesoscale and in thin section are the same structures observed by Reinen and Tullis (1995) in laboratory experiments. This implies that the deformation mechanisms and conditions were similar in the experiments and in nature. The presence of large zones of ductile deformation features cross-cut by brittle shears may indicate that the outcrop experienced stable fault creep producing S-C fabric, with occasional earthquakes, forming cataclasite-filled fractures.

CONCLUSION

Serpentinite along faults may be responsible for stable fault creep. In experiments, serpentinite has shown rate-weakening behavior at fast velocities and rate-strengthening at slower velocities. The deformation structures formed are Riedel shears and S-C foliation, respectively. The serpentinite on Sand Dollar Beach shows similar brittle and ductile deformation structures. By examining the outcrop on the mesoscale, in handsample, in thin section and using the scanning electron microscope, it can be confirmed that similar deformation structures occur on all levels of magnification. The similarity in deformation features in experiments and nature indicates that the fault zone on Sand Dollar Beach probably experienced stable fault creep with interspersed small earthquake events.

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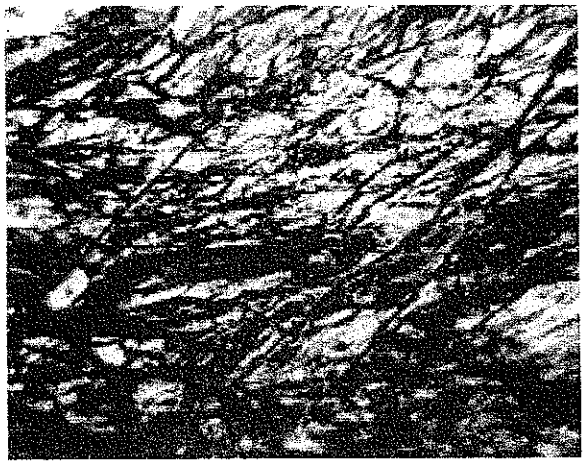

Figure 1a. Ductile deformation expressed as S-C foliation. (5 mm width) right lateral shear

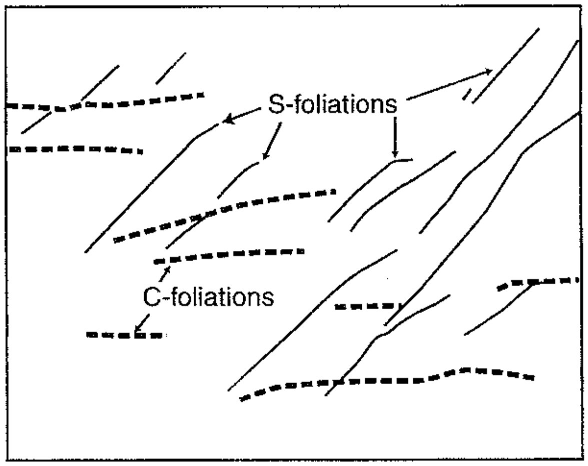

Figure 1b: Line drawing of S-C foliation.

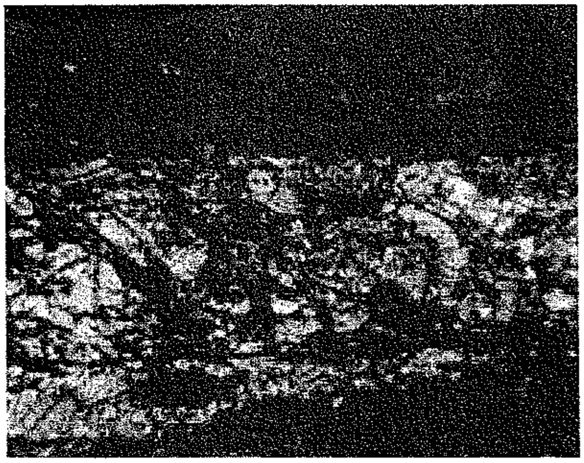

Figure 2a: Cataclasite in fault zone. (2.75 mm width) right lateral shear

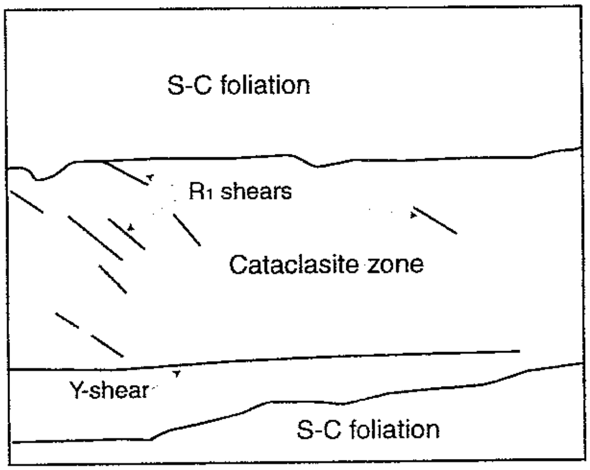

Figure 2b: Line drawing of Cataclasite zone.