Metamorphic geology and tectonic evolution of Franciscan Complex serpentinites, Big Sur region, central Coast Ranges, California

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INTRODUCTION

The Franciscan Complex (FC) is perhaps the best-studied example of a subduction-related accretionary melange. This terrane is typified by a matrix of chaotic terrigenous and pelagic sediments which are host to a variety of other rock types usually associated with oceanic crust (greenstone, basalt, gabbro) and high-*P*, low-*T* metamorphic environments (principally blueschist, but also amphibolite and eclogite) [*Blake and Jones*, 1981; *Platt*, 1986]. Blocks of serpentinite are invariably present within FC melange. Much research has been directed at such serpentinite blocks in that metasomatic alteration of ultramafic rocks during subduction may be analogous to the undefined processes which contribute to the creation of arc magmas in the suprasubduction-zone mantle wedge [i.e. *Bebout and Barton*, 1993; *Manning*, 1995, 1997; *Peacock*, 1996].

Another significant result of recent research is that serpentinite appears to accommodate aseismic fault creep similar to that observed for the San Andreas fault zone (SAFZ) [*Reinen et al.*, 1991, 1992]. In addition to serpentinite, the focussing of metamorphic fluids along the SAFZ and the mechanical weakness of the FC relative to neighboring crystalline basement rocks have also been proposed as possible mechanisms for fault creep along the SAFZ [i.e. *Allen*, 1968; *Irwin and Barnes*, 1975]. While any of these may be equally plausible, structural analysis of experimental serpentinite which exhibited creeping behavior during laboratory deformation indicates that creep is strongly correlated with mechanisms of ductile strain: distributed deformation, S-C fabric, and crystallographic-preferred orientation of Srp [*Reinen and Tullis*, 1995]. In contrast, experimental samples which exhibited instability and seismic potential during deformation are associated with brittle shearing (R_1, P, and Y shears) and the random orientation of grains [*Reinen and Tullis*, 1995]. These observations present criteria which may be used to tentatively evaluate the paleoseismicity of deformation recorded within serpentinized shear zones.

The primary focus of this study is to document the metamorphism, deformation, and fluid-rock interaction which have occurred during the tectonic evolution of the Sand Dollar Beach (SDB) and Jade Cove (JC) serpentinites. These data are significant to other microstructural studies of deformation within SDB and JC in that it may provide for approximations of *P-T* conditions accompanying deformational events. This study also documents the mineralogy and structure of contrasting deformational styles observed for an individual shear zone using electron microprobe (EMP) and high-resolution transmission electron microscopy (HRTEM). Results of these analyses may be further used to define geologic features associated with aseismic creep and seismic slip of sheared serpentinite.

METAMORPHISM

Franciscan Matrix. The SDB and JC serpentinites are enclosed within FC Coastal belt metapelitic flow melange. Unaltered samples of melange contain angular Ksp+Qtz+Plg clasts; however, sedimentary material is typically fully recrystallized to Chl+Wm in porphyroblastic texture. Two stages of porphyroblast growth are present within a sheared, foliated phyllosilicate and clay matrix. This foliation is also visible in outcrop, striking NNW and dipping steeply to the east. Abundant Qtz+Cc veins are present in FC exposures and near the JC locality typically interconnect with vein arrays present in the JC block. Subsequent alteration or thermal overprinting of FC flow melange is not observed within any sample.

SDB and JC Serpentinites. Relict phases identified in the SDB block include Ol, Cpx, Opx, and Chr; an assemblage which suggests a harzburgitic to lherzolitic peridotite protolith. Similar phases are not preserved within JC. Alteration of the original SDB peridotite is recorded by two distinct serpentinization events. The first of these has produced Srp mesh cells after olivine, chloritic rims surrounding Chr, and the incomplete hydration of Px to Srp. *Wooley* [1999] reports metamorphic diopside in association with this initial metamorphism. A second instance of serpentinization is recognized in preserved reaction fronts in hand sample and thin section. Behind this front, the second event has completed the alteration of Px to Srp and also recrystallized first-generation mesh cells to a fabric composed of Srp ribbons and interpenetrating grains. Magnetite was produced by both these events and modal amounts are significantly increased after complete serpentinization. Fragmentation of the block into meter-scale phacoids delineated by an anastomosing cleavage occurred in conjunction the serpentinization events. Significant alteration following these serpentinization events is not apparent within the SDB locality.

The JC serpentinite contains abundant evidence for SiO_2 metasomatism following serpentinization. Serpentinite/metapelitic melange contacts are marked by blackwall talc schists and numerous Qtz+Cc±Srp veins are present within the massive serpentinite. The addition of SiO_2 to the serpentinite appears to have made Srp and Brc metastable with respect to Chl and Tlc; Chl is the most abundant phase observed in both samples of massive serpentinite and blackwall schist. Similar Chr reaction textures and serpentinized Px crystals (Px-bastites) similar to those found in SDB occur throughout JC as well. Deformation similar to SDB is not present, but the JC block and another, inaccessible serpentinite body exposed to the south of JC appear to have been boudinaged on an extremely large scale.

Subduction-channel Metasomatism. The subduction channel is an ideal locality for the serpentinization of any ultramafic rock, in that 1) sediments within the subduction channel contain significant amounts of water trapped in pore spaces and within the crystal structure of clay minerals [*Cloos and Shreve*, 1988]; 2) subducted sediments, regardless of modal mineralogy, will buffer the concentration of aqueous SiO_2 within this fluid to near 100% [*Manning*, 1996]; and 3) high shear strains develop within the subduction channel, extensively deforming exotic blocks within melange, which increases porosity and permeability of exotic blocks and allows for the infiltration of potentially metasomatizing fluids [*Cloos and Shreve*, 1988]. This H_2O, SiO_2-rich fluid is in extreme disequilibrium with anhydrous, silica-poor peridotite which, when considered with the above factors, dictates that a serpentinization event would have occurred. The effects of infiltration metasomatism of the mantle wedge above subduction zones has been modeled by *Manning* [1995, 1997] using phase equilibria and thermodynamic relations between peridotite and an H_2O-SiO_2 fluid in the system MgO-SiO_2-H_2O (MSH). The sequence of metasomatic reactions outlined by *Manning* [1997] indicate that at first Srp+Brc will form from a peridotite without the noticeable addition of SiO_2. Once the peridotite is fully hydrated, Brc will react with aqueous silica to form Srp, thereby buffering the concentration of SiO_2. Following the complete conversion of Brc to Srp, the continued addition of an H_2O-SiO_2 fluid will result in the formation of talc at the expense of Srp. The modal mineralogy observed within the SDB and JC serpentinites appear to correlate well with these two reaction steps, respectively. This model provides the simplest explanation for the phase relations in both the SDB and JC serpentinites, suggesting that such a situation has occurred (Figure 1).

The enrichment of H_2O-mobile large ion lithophile elements (LILE) Cs and Rb in the JC serpentinite relative to SDB also indicates that metasomatism occurred within the subduction-channel. Cs and Rb have been shown to become partitioned into metamorphic fluids resulting from prograde metamorphism at deeper levels in subduction zones [*Bebout and Barton*, 1993]. H_2O-SiO_2 metasomatism of the JC block would have depleted these elements relative to SDB if they represented abundances inherited from the original peridotite. Therefore, LILE enrichment of JC indicates that the metasomatic fluid produced these observed changes (Figure 2). Depletions of Ca do occur in the JC block relative to SDB, which is a common result of serpentinization reactions [*O'Hanley*, 1996]. A greater extent of fluid-rock interaction in the JC serpentinite appears to have produced these chemical changes.

Figure 3 summarizes the subduction-channel metamorphism of the SDB and JC serpentinites.

MICROSTRUCTURAL ANALYSIS

A well-exposed shear zone present in the SDB serpentinite contains two distinct structural fabrics which developed following the uplift of the FC in this area. A broad zone of S-C fabric was found to be mostly recrystallized to large, homogenous grains composed of intermingled "packets" of antigorite+lizardite or chrysotile+lizardite, but never a collection of all three polymorphs together, as inferred from HRTEM imaging. A much more localized area of cataclastic deformation cross-cuts the S-C zone. EMP imaging of grains within the cataclasite indicates that the recrystallization of Srp did not accompany this event, but is instead composed of broken and granulated portions of the S-C fabric. This deformation was found to be almost pure chrysotile in HRTEM.

The preferred orientation of antigorite+lizardite crystals in the S-C fabric of this shear zone, observed at all scales (i.e. field, thin-section, EMP, and TEM) appears to indicate that this structural domain accommodated shear via distributed deformation and stable aseismic creep. The cataclastic domain, which cross-cuts the S-C fabric, does not show this preferred orientation, but rather is extremely random in orientation. Riedel (R_1) shears, the unoriented fabric, and random alignment of chrysotile crystals observed with TEM imaging suggest that this domain represents localized deformation and possible seismic slip.

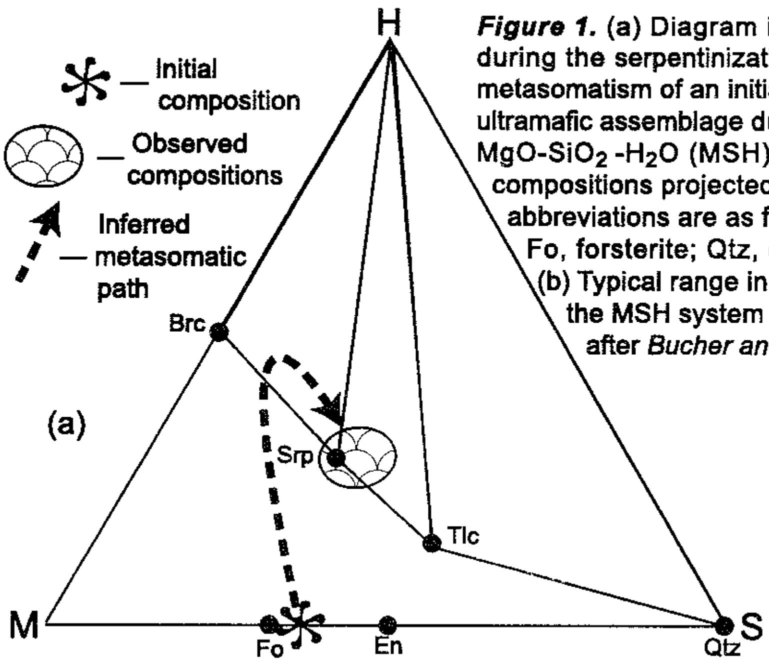
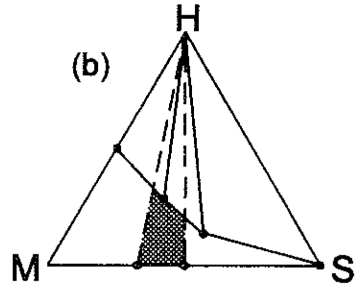


Figure 1. (a) Diagram illustrating chemical changes during the serpentinization and progressive SiO_2 metasomatism of an initially anhydrous 80% Fo + 20% En ultramafic assemblage due to an H_2O-SiO_2 fluid in the MgO-SiO_2-H_2O (MSH) system. Mineral and observed compositions projected by molar percent; mineral abbreviations are as follows: Brc,brucite; En, enstatite; Fo, forsterite; Qtz, quartz; Srp, serpentine; Tlc, talc. (b) Typical range in composition for mantle rocks in the MSH system (shaded region). Part (b) modified after *Bucher and Frey* [1994]).



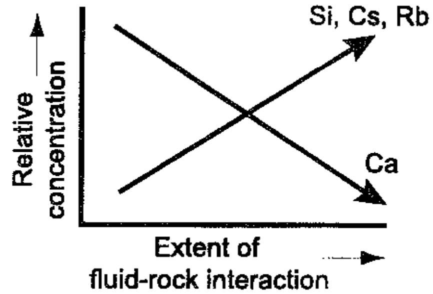


Figure 2. Schematic diagram illustrating observed changes in elemental abundances observed in SDB and JC serpentinites with extent of fluid-rock interaction as inferred from metasomatic reaction progress.

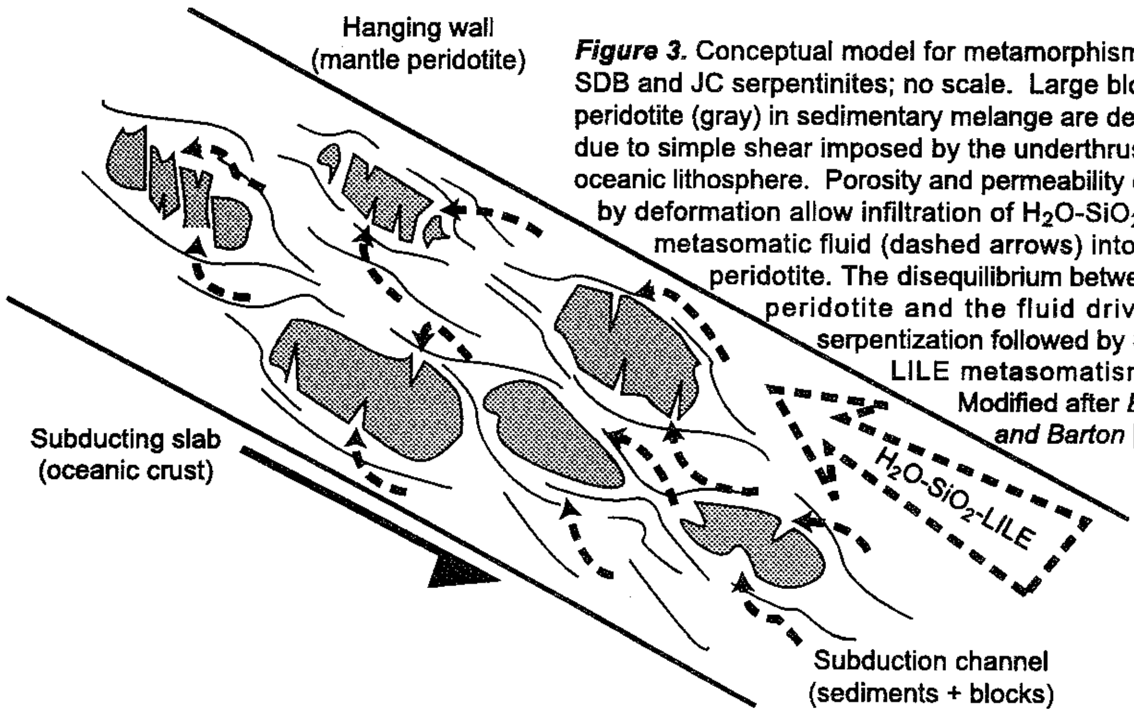


Figure 3. Conceptual model for metamorphism of the SDB and JC serpentinites; no scale. Large blocks of peridotite (gray) in sedimentary melange are deformed due to simple shear imposed by the underthrusting of oceanic lithosphere. Porosity and permeability created by deformation allow infiltration of H_2O-SiO_2-LILE metasomatic fluid (dashed arrows) into the peridotite. The disequilibrium between peridotite and the fluid drive serpentization followed by SiO_2-LILE metasomatism. Modified after *Bebout and Barton* [1989].

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