Paleoseismicity of Serpentinized Shear Zones in the Coast Range Ophiolite, California

Linda A. Reinen, Project Director
Department of Geology, Pomona College, Claremont CA 91711

Cameron Davidson
Department of Geology, Beloit College, Beloit WI 53511

INTRODUCTION

Segments of some large faults like the San Andreas accumulate slip without experiencing large earthquakes. Stable fault creep has been observed on such faults for years, but the underlying cause of this behavior has been unknown. Recent laboratory experiments on serpentinite have identified a likely mechanism for the stable creep observed on natural faults. Analysis of the experimentally deformed fault zones indicates that specific microstructures develop during the experiments which can be directly correlated to the slip stability of the fault. Now, for the first time ever, we have the tools available to identify whether ancient serpentinized faults experienced earthquakes or stable fault creep.

Serpentine is found on many active faults and may be responsible for the observed aseismic behavior of segments of these faults. Laboratory experiments indicate that serpentinite displays two distinct modes of slip as a function of sliding velocity: stable, aseismic slip at low velocities (comparable to typical plate velocities), with the potential for unstable slip (analogous to an earthquake) at higher velocities (e.g., Reinen et al., 1994). This is in contrast to what is observed for other crustal rocks, such as granite and quartzite, which have the potential for unstable slip even at low plate velocities. The presence of serpentine on crustal faults should thus promote stable, aseismic creep even at depths shallow (and cold) enough to experience earthquakes.

Can the paleoseismicity of ancient serpentinized faults be determined from present-day observables? Previous researchers have conjectured about the mechanical behavior of serpentinized faults using observations of the microstructures developed within the fault zone (Norrell et al., 1989; Hoogerduijn Strating and Vissers, 1994). They have identified distinct microstructures which they interpret to form under either seismic or aseismic conditions. By necessity, these researchers have had to make assumptions about the mechanical regimes within which the observed microstructures formed. Recent analysis of microstructures developed in serpentinite gouge during controlled laboratory experiments indicates a correlation of specific microstructures with well-constrained mechanical behavior (Reinen and Tullis, 1995). Specific, identifiable microstructures give a clear indication of the mechanical behavior of the serpentinite: aseismic fault slip leads to distributed deformation and a uniform preferred orientation of serpentine grains (e.g. S-C fabric, Figure 1), while earthquake-generated slip leads to localized deformation on discrete planar surfaces (e.g. Riedel shears, Figure 2). Using these laboratory-developed microstructures for comparison, it is now possible to infer the dominant mode of slip (seismic *vs.* aseismic) of natural serpentinized faults from the structures developed within the fault zone.

In this project, students conducted a detailed analysis of a serpentinized portion of the Coast Range Ophiolite along the central California coast (Figure 3). The study area is part of the Sur-Nacimiento fault zone, a system of faults thought to have been the active plate boundary prior to initiation of the San Andreas Fault. We focused on two specific study sites, both of which have good exposures of deformed serpentinite within the sea cliffs: (1) Sand Dollar Beach where a 4 meter high shear zone is exposed within a massive serpentinite; and (2) Jade Cove where massive serpentinite is separated from graywacke by a large (~5 meter) wide gouge-filled fault zone. Student participants characterized the metamorphic and deformational history of these areas, and were able to infer the paleoseismic behavior of this section of the ancient plate boundary.

OVERVIEW OF PROJECT ACTIVITY

Participants in this project spent approximately two weeks in the field mapping and sampling portions of the Coast Range Ophiolite exposed along the central California coast. While in the field we camped under the redwoods at Limekiln campground, 7 miles north of the field site. Following the field work, project participants returned to Pomona College and prepared chips for thin sections, started compositional analysis using an X-ray diffractometer (XRD), converted their field maps to Adobe Illustrator documents, and conducted extensive library research.

The two faculty and six students on this project met again in February 1999 at Pomona College for a group workshop (see abstract in this volume). Four students arrived in Claremont a few days prior to the workshop to use the SEM at the University of California at Riverside.

STUDENT PROJECTS

Marin Byrne (Carleton College) focused on the serpentinized shear zone exposed along San Dollar Beach. Together she and Heidi Reeg (Pomona College) mapped the length of the exposed portion (~150 m) of this shear zone. In the field, Marin focused her attention on two ~1 m^2 areas which contained endmembers of the deformation styles present in the outcrop, including both brittle and ductile features as well as varying amounts of finite strain. She collected samples of all of these features for analyses. Marin analyzed the compositional and microstructural details of the different deformation features in her focus areas using an X-ray diffractometer, optical microscope, and a scanning electron microscope. She has identified some very interesting relations between cataclastic and distributed deformation features.

Rachel Cahill (Beloit College) examined compositional and structural details in the Jade Cove field area. Together, Rachel and Joe Dzuban (College of Wooster) mapped the large scale features of the major gouge-filled fault zone in Jade Cove, including structural features, lithologic variations of the wall rocks, and color variations within the gouge (following the method of Chester and Chester, 1997). Rachel identified both brittle and ductile features, which she analyzed at several scales: outcrop, thin section, and scanning electron microscopic scale. Using these techniques, Rachel found an intriguing relationship between composition and deformation style.

Joseph Dzuban (College of Wooster) identified the paleoseismic nature of the fault zone at Jade Cove. Initially, he and Rachel Cahill (Beloit College) mapped the structures and lithologies of the exposed portion of the gouge-filled fault zone and surrounding wall rocks. Joe then turned his attention to the nature of the deformation fabrics observed at hand sample, optical, and SEM scales. He identified features which suggest a complicated seismic history of this ancient fault, which includes both earthquakes and fault creep events. Joe identified a scale-dependence of the deformation features (brittle *vs.* ductile) which complicates the interpretation of the seismic history.

Heidi Reeg (Pomona College) examined deformation style and composition of the shear zone in Sand Dollar Beach. Together with Marin Byrne (Carleton College), she mapped the exposed length of the shear zone. Heidi focused her attention on two ~1 m^2 areas which she mapped in greater detail. These two focus areas contain several examples of the different deformation styles (localized and distributed deformation), as well as the range of potential compositional variations found within the shear zone. Heidi collected several samples of each deformation style and lithologic composition. She conducted compositional and microstructural analyses using a petrographic microscope, an X-ray diffractometer, and a scanning electron microscope. From her study, Heidi was able to infer the paleoseismicity of the shear zone exposed along Sand Dollar Beach.

Robert King (College of Wooster) investigated the metamorphic history of the ultramafics in order to provide a tectono-metamorphic framework for the microstructural studies at Sand Dollar Beach and Jade Cove. Robbie also investigated the mineralogic composition of different deformation fabrics from within the shear zone at Sand Dollar Beach. In the field, Robbie collected numerous samples including rocks reflecting varying degrees of metamorphism, and mineralized veins and shear zones in order to characterize the metamorphic fluid-rock interactions. Robbie analyzed his samples via petrographic microscope, electron microprobe, and high-resolution transmission electron microscope. From his analyses, Robbie has suggested a model for the metamorphism which accounts for the differences in mineralogy found in the two study areas. From his TEM analyses, he has identified the serpentine polytypes present within the cataclastic and S-C fabric domains of the Sand Dollar Beach shear zone, which has implications for the seismicity of the shear zone.

Ryan Wooley (Colorado College) examined the petrography and geochemistry of the massive serpentinites exposed at both the Sand Dollar Beach and the Jade Cove study areas in order to identify the protoliths and metamorphic histories of the two areas. In the field, Ryan collected samples from the massive serpentinite blocks which preserved relic protolith textures. Ryan identified mineral phases in thin section and using a scanning electron microscope. He obtained whole rock major and minor element data from X-ray fluorescence analysis of his samples. Ryan identified important differences between the serpentinites of the two areas, and has suggested several possible models to account for those differences.

PROJECT VISITORS, ASSISTANTS, AND FAMILY

In the field, two faculty advisors, a visiting scientist, a camp assistant and family members visited us in the field. Dr. Jeff Noblett (Colorado College), Dr. David Bice (Carleton College), Jen Macalady (UCDavis) provided valuable advice and assistance during their visits. Susan Nielsen (Pomona College, class of 2000) was our camp cook and general field assistant. The Davidson family (Karen, Carly, and Peter) were our camp and playtime buddies. Other family members participated in the project: Cam's parents offered to fly us over our field area, and we stayed at Linda's parents house one night on the way to the coast. On a day off, Dr. David Clague hosted us on a tour of the Monterey Bay Aquarium Research Institute.

At Pomona College, Eric Riggs (UCRiverside) taught us about the fractal nature of faults and fault gouge. Jessica Jager (Pomona College, class of 2000) lead us in the use of the XRD, and Carrie Elliott (Carleton College, class of 1998) assisted us with computing and supply needs. Dr. Eric Grosfils (Pomona College), took us on a guided tour of the Jet Propulsion Lab in Pasadena. During the tour, we met with several of the scientists working on the Galileo mission to Jupiter, and a scientist working with AVIRIS, an aircraft remote sensing instrument to study earth

OUTSIDE CONSULTANTS

This project involved a high degree of technical analyses. Dr. Krassimir Bozhilov (Analytical Electron Microscopy facility, UCRiverside) helped immensely with the SEM analyses of M. Byrne, J. Dzuban, H. Reeg, and R. Wooley; Dr. Ken Livi (Johns Hopkins University) worked with R. King on his HR-TEM and microprobe analyses; Dr. Fred Chester (Texas A&M University) provided advice in the collection of fault gouge; Act Labs in Ontario, Canada provided the XRF analyses for R. Wooley.

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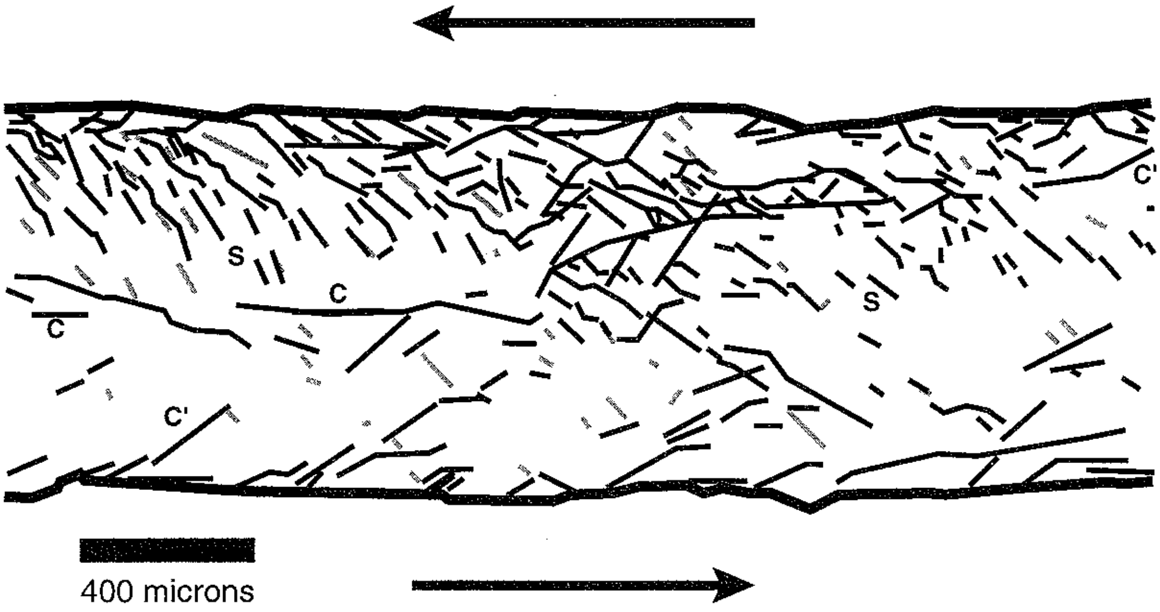

Figure 1. Map of the S-C-C' fabric developed during an experiment on chrysotile gouge. Heavy black lines indicate the edge of the gouge layer; thin black lines are fractures within the gouge; gray lines indicate the long axes of asymmetric grains. Experimental conditions: 25 MPa normal stress, 49 mm total displacement.

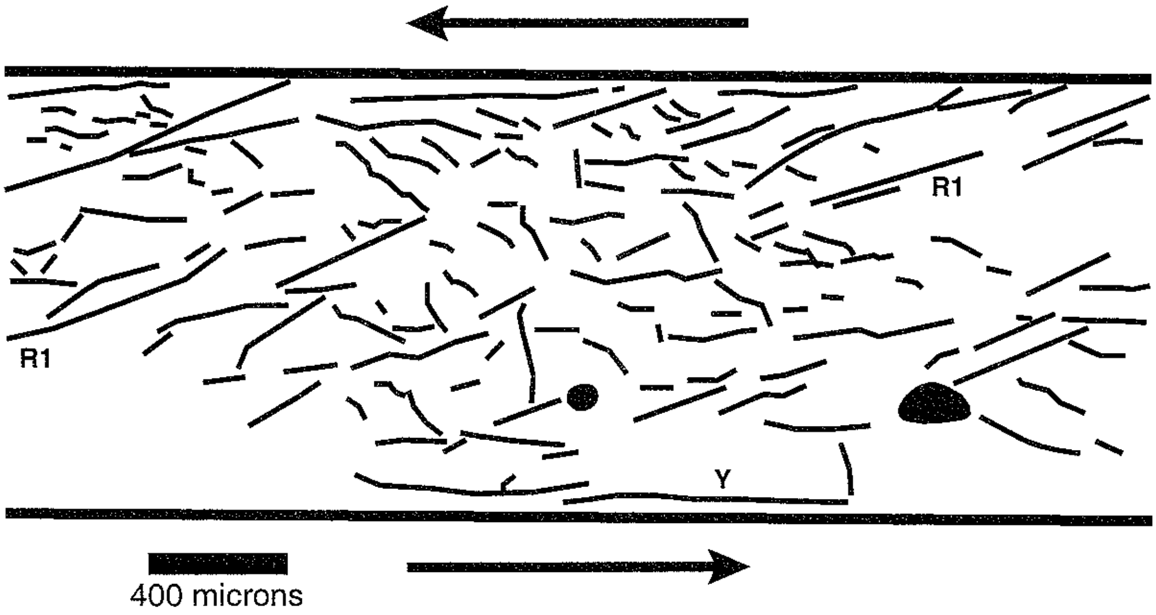

Figure 2. Map of the Riedel shears developed during an experiment on antigorite gouge. Heavy black lines indicate the edge of the gouge layer; thin black lines are fractures within the gouge. Experimental conditions: 25 MPa normal stress, 222 mm total displacement.

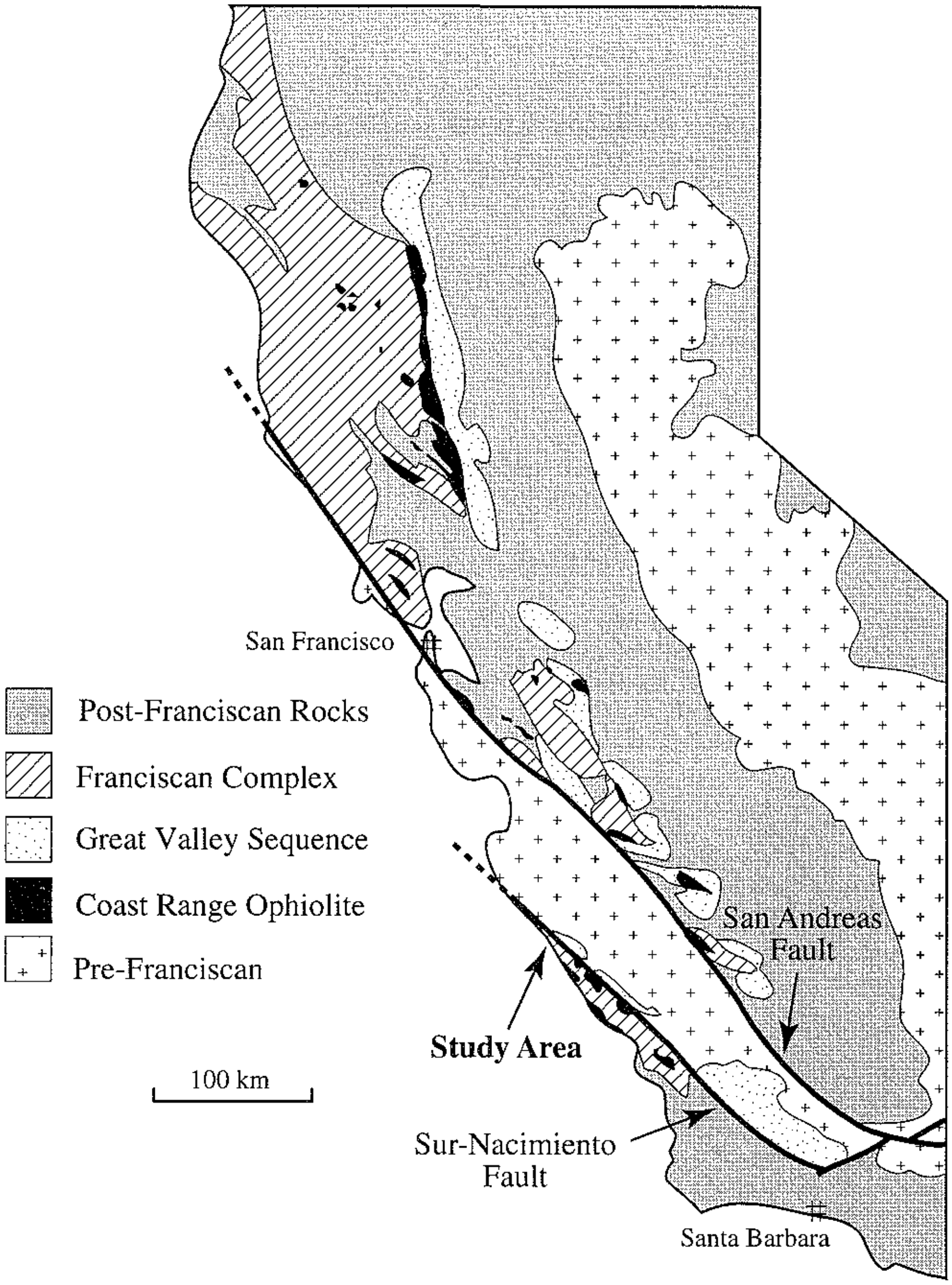

Figure 3. Tectonic map of central California, showing the location of our study area. (Modified by R. Cahill after Hopson et al., 1981)

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

Marin J. Byrne
Department of Geology, Carleton College, 300 North College St., Northfield, MN 55057
Faculty sponsors: Linda Reinen, Pomona College; David Bice, Carleton College

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