Rock Properties and Structure Within the San Andreas Fault Observatory at Depth (SAFOD) Borehold, Northwest of Parkfield, California: In Situ Observations of Rock Deformation Processes and Fluid-Rock Interactions of the San Andreas Fault Zone at ~ 3 km Depth

Kelly Keighley Bradbury
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ROCK PROPERTIES AND STRUCTURE WITHIN THE SAN ANDREAS FAULT
OBSERVATORY AT DEPTH (SAFOD) BOREHOLE NORTHWEST OF PARK-FIELD, CALIFORNIA: \textit{IN SITU} OBSERVATIONS OF ROCK DEFORMATION PROCESSES AND FLUID-ROCK INTERACTIONS OF THE SAN ANDREAS FAULT ZONE AT \textasciitilde 3 KM DEPTH

by

Kelly Keighley Bradbury

A dissertation submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY in

Geology

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\textbf{UTAH STATE UNIVERSITY} \\
Logan, Utah \\
2012
ABSTRACT

Rock Properties and Structure Within the San Andreas Fault Observatory at Depth (SAFOD) Borehole, Northwest of Parkfield, California: *In Situ* Observations of Rock Deformation Processes and Fluid-Rock Interactions of the San Andreas Fault Zone at ~ 3 km Depth

by

Kelly Keighley Bradbury, Doctor of Philosophy

Utah State University, 2012

Major Professor: Dr. James P. Evans
Department: Geology

This project examines the composition, structure, and geophysical properties of rocks sampled within the San Andreas Fault Observatory at Depth (SAFOD) borehole drilling experiment near Parkfield, California. Cuttings, sidewall cores, spot-core, and whole-rock core are examined from the meso- to micro-scale to characterize the near-fault environment at shallow crustal levels (0-4 km) along the central segment of the San Andreas fault. The central segment deforms by continuous aseismic creep and microseismicity. An integrated approach utilizing core-logging, detailed structural core mapping, petrology, microstructural analyses, whole-rock geochemistry, borehole geophysics, and analog field studies is followed.
At SAFOD, fractured granitic rocks and arkosic sediments are identified west of the San Andreas fault zone on the Pacific Plate; whereas sheared fine-grained sediments, ultrafine black fault-related rocks, and serpentine-bearing fault gouge are present within and northeast of the fault zone on the North American Plate. Here, the fault consists of a broad zone of variably damaged rock containing localized zones of highly concentrated shear that often juxtapose distinct rock-types. Two zones of serpentine-bearing clay gouge, each meters-thick are found in two locations where active aseismic creep was identified in the borehole. The gouge is composed of Mg-rich clays, serpentine (lizardite ± chrysotile) with notable increases in magnetite, and Fe-, Ni-, and Cr-oxides/hydroxides and Fe-sulfides relative to the surrounding host rock. Organic carbon is locally high within fractures and bounding slip surfaces. The rocks adjacent to and within the two gouge zones display a range of deformation including intensely fractured regions, block-in-matrix fabrics, and foliated cataclasite structure. The blocks and clasts predominately consist of competent sandstone and siltstone embedded in a clay-rich matrix that displays a penetrative scaly fabric. Mineral alteration, veins, fracture-surface coatings, and slickelined surfaces are present throughout the core, and reflect a long history of syn-deformation and fluid-rock reaction that contributes to the low-strength and creep in the meters-thick gouge zones.

Evaluation of borehole geophysical data and elastic modulii for the lithologic and structural units identified in the SAFOD Phase 3 core reveal a correlation between composition and textures and the structural and/or permeability architecture of the SAF at SAFOD. Highly reduced velocity and elastic modulii surround the two serpentine-
bearing gouge zones, the Buzzard Canyon fault to the southwest, and another bounding fault to the northeast. Velocity and elastic moduli values on the Pacific Plate or southeast of the active fault trace intersected by SAFOD are much higher relative to the values measured on the North American Plate, or northeast of the fault trace. Within and adjacent to the two active gouge zones, the rock properties are highly variable over short distances, however, they are significantly lower relative to material outside of the fault zones.

This research contributes critical evidence for rock properties and slip behavior within an active plate boundary fault. Results from this research and the SAFOD experiment help to constrain numerous hypotheses related to fault zone behavior and earthquake generation within central California.
PUBLIC ABSTRACT

Rock Properties and Structure Within the San Andreas Fault Observatory at Depth (SAFOD) Borehold, Northwest of Parkfield, California: In Situ Observations of Rock Deformation Processes and Fluid-Rock Interactions of the San Andreas Fault Zone at ~ 3 km Depth

by

Kelly Keighley Bradbury, Doctor of Philosophy
Utah State University, 2012

Major Professor: Dr. James P. Evans
Department: Geology

The San Andreas Fault Observatory at Depth (SAFOD) is a scientific drilling experiment situated along the central creeping segment of the San Andreas Fault, near Parkfield, California, and north of a segment of the fault that has experienced large historical earthquakes. Drilling into active fault zones allows scientist’s to examine in situ rock samples and to record real-time data.

The main goal of this study is to characterize the geologic setting and rock properties of the San Andreas fault at ~ 3 km depth in the SAFOD borehole. In this region, the fault deforms nearly continuously through aseismic creep and small earthquakes. By sampling and characterizing the rocks from this location of the fault, we can begin to identify the features associated with fault-related deformation processes in
the shallow crust; revealing the nature of the earth’s crust in the near-fault environment and yields insight into the mechanisms associated with earthquake generation along an active strike-slip fault. It is also useful to seismologists for developing well-constrained, predictive earthquake models.

Project costs are ~ $175,000 funded primarily by NSF-Earthscape grant EAR-0454527 to Dr. James P. Evans with additional support provided by the Geology Department and national scholarships to the student. Costs are associated with travel to examine core at the U.S.G.S. Core Lab in Menlo Park, CA and the IODP Gulf Coast Repository in College Station, TX; lab work, and sample processing and analyses at USU and Washington State University; field work travel plus an assistant, and collection and processing of field samples; and expenses associated with Teaching and Research Assistantships appointed to Kelly K. Bradbury during the course of this research.
ACKNOWLEDGMENTS

I am grateful to my advisor, Dr. James P. Evans, for guiding me through the process of completing a dissertation. I would like to thank Dr. Evans for his endless patience, understanding, financial/mental/emotional support, and his unique ability to encourage and mentor his students while encouraging complete autonomy in their work. My Committee Members: Anthony Lowry, John Shervais, Susanne Janecke, and Janis Boettinger, not only provided significant contributions to my education and to the improvement of this dissertation, but have provided excellent examples of scientific integrity and inquiry, the importance of maintaining a sense of humor within the rigors of academia, and are all truly an inspiration. I appreciate numerous insightful discussions concerning the SAFOD Project with Fred and Judi Chester from Texas A&M. I would also like to thank the rest of the Geology Department Faculty and Staff, especially Marsha Hunt and Jean Daddow for their neverending support and assistance.

Thirteen Thank Yous to my family, especially Bill and Ember, for their love, support, and endless patience. Also to my four-legged friends, whose love and joy for life and runs on the trails helped me maintain sanity throughout graduate school. To all of my friends, running partners, and USU Geology graduate students, I appreciate your comradery, flow of knowledge and endless humor.

The majority of this project was funded by an NSF-Earthscope grant EAR-0454527 to Dr. Evans with additional support from several student research grants and/or scholarships from the Society for Exploration Geophysicists (SEG) Foundation, the
Society for Petrophysicists and Well Log Analysts, the AAPG Foundation, DOSECC, the GDL foundation, Peter McKillop Scholarship, and the USU Geology Department.

Kelly Keighley Bradbury
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CHAPTER 1
INTRODUCTION

Much of our geologic understanding of fault-related rock properties in the upper 2–15 km of the Earth’s crust is based on sampling of exhumed faults, laboratory experiments, and geophysical models (Sibson, 1977, 1986; Scholz, 2002; Handy et al., 2007; Wibberley et al., 2008). The composition and structure of fault zones, along with deformation mechanisms, fluid-rock interactions, and evolution of fault zones in the context of the seismic cycle have been examined in a variety of settings (e.g. Chester and Logan, 1986; Cooper and Norris, 1994; Faulkner et al., 2003; Griffith et al., 2008; Holdsworth et al., 2001; Kondo et al., 2005; Schulz and Evans, 2000; Wibberley and Shimamoto, 2003). These studies, among many others, have revealed a great deal about the across-strike structure of fault zones, with the recognition that faults often are comprised of a damage zone, a core and/or gouge zone, and one or more principal slip surfaces (Caine et al., 1996; Chester and Logan, 1986; Schulz and Evans, 1998; Figure 1-1). The thickness, nature, and distribution of these fault components may vary along a single fault, and vary between fault types and settings.

At the boundaries of or within a damage zone surrounding a particular fault, which typically range in width from meters to tens of meters up to 1 km for large-displacement faults (Cochran, 2009; Kim et al., 2004) one or more fault cores (centimeters up to 1 m thick) consist of fine-grained cataclasite, foliated clay gouge, or breccia. Fine- to micro-scale structures of the central core and/or fault gouge may show extremely narrow and localized slip surfaces representing much of the slip along the fault (Chester et al., 1993; Caine et al., 1996). Alternatively, distributed zones of shear and/or
fault gouge comprised of heterogeneous mixtures of competent and incompetent rocks surrounded by foliated fabrics may form broad-scale shear zones or a mixed-mode of deformation is observed (Fagereng and Sibson, 2010; Faulkner et al., 2003; Wibberley and Shimamoto, 2003). Clay content and mineralogical phases of the central fault core gouge may also vary and may influence fault zone behavior locally as increases in the total clay content can decrease the overall frictional strength of a fault (Numelin et al., 2007) which are related to the strength of the fault, an important issue to resolve for understanding the state of stress and fault zone behavior in the crust (Lachenbruch and Sass, 1980; Rice, 1992; Zoback et al., 1987). Fault strength varies spatially (e.g. Erickson and Wiltschko, 1991; Townend and Zoback, 2001) and temporally (Niu et al., 2003) and reflects the maximum stress a material can support, or rather its frictional resistance to slip, given the fault’s mechanical properties and the surrounding physical and chemical conditions within the crust (Paterson and Wong, 2005; Scholz, 2002). Composition can play a significant role in the frictional properties and strength of a fault (Chester and Logan, 1986; Ikari et al., 2011; Numelin et al., 2007; Schulz and Evans, 1998; Summers and Byerlee, 1977). For example, studies on phyllosilicate-bearing fault gouge (such as identified at SAFOD, Schleicher et al., 2006; 2009) and foliated cataclasite indicate that slip occurs along mm-thick surfaces, on which neomineralized clay grains grow (Schleicher et al., 2010). Studies of exhumed fault zones support the observation that weakening mechanisms begin at the grain-scale (Holdsworth, 2004; Wibberley et al., 2008), however, the frictional properties within a particular fault may vary spatially and temporally, especially in large displacement active fault zones due to
the complex interplay between composition, deformation processes, temperature, grain size, fluid-rock reactions (Evans, 1988; Vroiljk and van der Pluijm, 1999), structural and permeability anisotropy (Evans et al., 1997; Haines et al., 2009; Morrow et al., 1984), and pore fluid pressures (Faulkner and Rutter, 2003; Faulkner et al., 2003; Shimamoto and Logan, 1984; Sleep, 1995; Warr and Cox, 2001; Wibberly, 2002). Well-developed foliated fabrics and fine-fracture coatings may also contribute to slip or glide along these surfaces and lead to fault zone weakening (Colletini et al., 2009; Haines et al., 2009; Ikari et al., 2009; Neimeijer et al., 2010; Wintsch et al., 1995).

The San Andreas Fault Observatory at Depth (SAFOD; http://www.earthscope.org/observatories/safod) is a scientific drilling experiment stationed northwest of Parkfield, California (Figure 1-2) at the transition from the creeping segment of the San Andreas Fault (SAF) to the northwest and the Parkfield rupture segment to the southeast.

The SAFOD project is one component of the EarthScope initiative, an earth science program funded by the National Science Foundation (Hickman et al., 2007). Observations via drilling into active faults help to overcome issues associated with using exhumed fault zones as a proxy for the analysis of in situ processes and mechanical behavior of seismically active faults (Hung et al., 2005; Isaacs et al., 2008; Ohtani et al., 2000), and can tell us much about the deformation processes within these faults (Ikeda, 2001; Matsuda et al., 2001; Moore et al., 1995). Drilling into active faults provides information that contributes to understanding the types of chemical and physical processes occurring during seismic or interseismic cycles at shallow crustal levels (Hickman et al., 2004; Tobin et al., 2007). Direct drill-based observations also reduce the
potential ambiguity in interpretation of primary textures and geochemical signatures in faults, which may become obscured due to overprinting mechanisms associated with exhumation and weathering (Isaacs et al., 2008).

Figure 1-1. Generalized fault zone model where the fault consists of an outermost damage zone, inner damage zone, and central fault core (after Caine et al., 1996 and Ganerod and Braathen, 2008). Inset image shows a simplified model for a strike-slip fault zone at shallow crustal levels in phyllosilicate-rich rocks (after Faulkner et al., 2003); similar to the SAF at SAFOD with a main fault core comprised of anastomosing fractures and slip surfaces surrounded by an innermost intensely fractured damage zone and possible blocks of wall rock and/or mixed blocks entrained within the fault zone.
Figure 1-2. Physiographic location and setting of the San Andreas Fault Observatory at Depth (SAFOD) Project (http://www.earthscope.org/observatories/safod).

Geophysical research of fault zone structure spans a variety of scales and techniques from surface to subsurface (borehole) surveys, laboratory experiments, and inverse modeling. Commonly, fault zones are modeled using simplifying assumptions,
such as isotropic and homogenous rock properties rather than heterogeneous and anisotropic, as is typical in natural settings (Fukuyama et al., 2003).

Geologic observations and borehole geophysical data collected at SAFOD (Boness and Zoback, 2006) provide a more complete data set of physical rock properties, fault-related damage, and structure. With careful consideration, these data present an opportunity to calculate better estimates for physical properties of fault-related rocks that are necessary to constrain geophysical models. Borehole-scale geologic observations can be correlated to surface (Catchings and Rymer, 2002; McPhee et al., 2004) and borehole geophysical data (Boness and Zoback, 2004, 2006; Zoback et al., 2010) and provide clues to the fine-scale velocity structure and processes controlling earthquake nucleation and/or energy adsorption within the SAF.

Several studies show that in general, the near-fault environment is one of reduced seismic velocities and increased attenuation of seismic waves compared to the surrounding less-deformed host rock (Li et al., 1994; Li and Vidale, 1996; Paterson and Wong, 2005). At SAFOD, magnetotelluric and seismic reflection surveys (Unsworth et al., 1997; Unsworth and Bedrosian, 2004) showed a zone of low resistivity east of the surface trace of the SAF, which also correlated to a similar region of reduced seismic velocities (Hole et al., 2006; Thurber et al., 2004). Based on modeling of fault-guided waves, Li and Malin (2008) proposed that the SAF near SAFOD is comprised of a two-layered, downward-tapering fault zone geometry at SAFOD with a ~40 m wide core of ~40% reduced velocity surrounded by ~200 m wide damage zone of ~25% reduced velocity. Seismic and geodetic evidence also suggest that anomalous strain and damage
may occur within active fault zones over the earthquake cycle (Fialko, 2004; Li and Malin, 2008). This concept is referred to as fault zone compliance (Chen and Freymueller, 2002; Cochran et al., 2006; 2009; Fialko, 2004; Fialko et al., 2002; Li and Malin, 2008), and is described by ~1-2 km wide long-lived, fault zones that show a reduction in velocities and elastic moduli compared to the surrounding crust (Hearn and Fialko, 2009; Li and Malin, 2008).

Drilling, monitoring, and sampling efforts at SAFOD are designed to test fundamental questions regarding fault zone behavior based on observations of in situ conditions (Hickman et al., 2004; http://www.earthscope.org/observatories/safod). The SAFOD project provides a unique opportunity to examine the detailed composition, structure, and permeability architecture of the near-fault environment and to compare these observations to the geophysical measurements made within an actively creeping segment of the fault where microseismicity currently nucleates, thus, helping to define the processes associated with active slip and fault zone behavior. A wide variety of data has been collected at the SAFOD from two closely spaced boreholes, the 2.1 km deep vertical SAFOD Pilot Hole and the deviated main 3.99 km long SAFOD borehole (~15 m map distance separation). These data, along with continued testing of in situ stress, permeability and pore pressure conditions, analyses of frictional behavior of fault zone materials, and the determination of the physical properties and chemical processes observed in the fault zone, will provide constraints of the potential interplay of deformation mechanisms in seismogenic and creeping faults.
At SAFOD, a total of approximately 41 m of spot core was collected from three separate sidetrack locations off of the main borehole during Phase 3 in 2007 (http://www.earthscope.org/observatories/safod). Core characterization methods include the identification and spatial distribution of lithostratigraphic and structural units preset within the core, petrography and microstructural analyses, mineral chemistry, including X-Ray Diffraction techniques, whole-rock geochemistry (X-Ray Fluorescence) of cuttings and core, and a comparison of these results to borehole geophysical measurements, including calculations of elastic moduli for each lithostratigraphic/structural unit.

Drilling and sampling at SAFOD has revealed a highly complex structural and permeability architecture in the near-fault environment comprised of numerous lithostratigraphic and/or structural units including fractured arkosic sandstones and shale west of the SAF zone on the Pacific Plate, and sheared fine-grained sedimentary rocks, ultrafine black fault-related rocks, and phyllosilicate-rich fault gouge within and east of the fault zone on the North American Plate (Bradbury et al., 2007; 2011; Draper, 2007; Holdsworth et al., 2011; Solum et al., 2007; Springer et al., 2009; Wiersberg and Erzinger, 2008; 2011). The fault zone sampled near ~ 3 km depth at SAFOD consists of a broad region of variably damaged rock containing localized zones of highly concentrated shear that often juxtapose distinct protoliths. Two zones of m-thick, serpentinite-bearing fault gouge are associated with casing deformation and are interpreted to represent actively creeping zones of the SAF (Zoback et al., 2010). The clay-rich gouge matrix is primarily composed of Mg-rich clays, serpentinite (lizardite ± chrysotile) with notable
increases in mineralization such as magnetite, and Ni-Cr-oxides/hydroxides relative to the surrounding host rock. The rocks immediately surrounding the two creeping gouge zones display a range of deformation including fractured protolith, block-in-matrix textures, and foliated cataclasite structure. The blocks and clasts predominately consist of sandstone and siltstone embedded in a clay-rich matrix that displays a penetrative scaly fabric. Mineral alteration, veins and fracture-surface coatings are present throughout the core, and reflect a long history of syn-deformation and/or fluid-rock reactions that contribute to aseismic deformation in the meters-thick gouge zones.

The primary contribution of this research is to identify and characterize the variation and distribution of parameters such as composition, texture, chemical alteration, and shear surface distribution in detail (sub-meter to micrometer scale) across the SAF as drilled and sampled at SAFOD. Core-based geological studies of cuttings, sidewall cores, spot core, and whole-rock core coupled with borehole geophysical measurements, are integrated to develop a plausible geologic model surrounding the SAFOD borehole at ~ 1-4 km depth (Bradbury et al., 2007; 2009; 2011; Bradbury and Evans, 2010).

A comparison of the SAFOD rocks to exhumed analog rocks from accretionary sedimentary rocks of the Franciscan Formation (Bailey et al., 1964) are also considered in an effort to constrain the potential range of geochemical and physical processes associated with deformation and fluid-rock interactions in fine-grained phyllosilicate-rich materials. This research is significant because it examines the material properties and structures of rocks within an active fault at scales that affect or are affected by seismic slip and at a location in which microearthquakes nucleate in the shallow crust.
Furthermore, results presented here will contribute to understanding processes associated with fault zone deformation mechanisms and fluid-rock interactions in the shallow crust. Integration of borehole geophysical data with geological observations at SAFOD allows for a more robust comparison between the spatial distribution of chemical and physical rock properties and measurable variations in seismic velocities and elastic moduli within near-fault environment. It is important to note, however, that due to the nature of drilling at SAFOD, the Phase III whole-rock core collected represents only a small portion of the nearly ~ 1 km broader zone of the SAF (Cochran et al., 2009) and that the spatial and temporal evolution of a fault zone will influence fault properties measured during specific in situ sampling intervals, thus, long term monitoring and additional coring is necessary to constrain the complex subsurface structure and numerous hypotheses related to fault zone behavior and seismic activity along the SAF.

The research presented in this dissertation focuses on several aspects of fault zone structure and composition as revealed by rocks sampled and tested by the SAFOD drillhole, and the results are presented in four chapters. Chapter 2, published as Bradbury et al. (2007), documents the lithology and deformational textures in host rocks and distribution and character of at least 5 fault strands based on analyses of drill cuttings from the SAFOD main hole and Pilot Hole. The work in Chapter 2 also depicted a geologic model for the fault zone based on the available data at the time. The lithology and internal structure of SAFOD Phase 3 core is examined in Chapter 3 and is published as Bradbury et al. (2011). Chapter 4 is entitled “Micro-scale composition and texture associated with deformation in the San Andreas Fault at SAFOD: Evidence for Seismic
and Aseismic Processes” and is written as a shorter, companion paper to Chapter 2 that presents more geochemical data and focuses on composition and structure variations at the micro- to submicron-scale. Chapter 5 represents the next phase of continuing research related to this dissertation and is therefore written in a report-style format. This work examines the geophysical rock properties of the San Andreas Fault system at SAFOD and will be submitted for publication in the near future. In addition to these analyses, work related to this dissertation contributed to the Phase 3 Core Photo Atlas Report (http://www.earthscope.org/observatories/safod) and data for two Undergraduate Research Projects: Colter Davis (USU 2009) and Tamara Jeppson (USU 2010), the latter resulting in a publication on the relationship between geophysical properties, mineralogy, geochemistry, and fault structure (Jeppson et al., 2010).

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CHAPTER 2

MINERALOGIC AND TEXTURAL ANALYSES OF DRILL CUTTINGS FROM THE
SAN ANDREAS FAULT OBSERVATORY AT DEPTH (SAFOD) BOREHOLES:
INITIAL INTERPRETATIONS OF FAULT ZONE COMPOSITION AND
CONSTRAINTS ON GEOLOGIC MODELS

Abstract

We examine drill cuttings from the San Andreas Fault Observatory at Depth (SAFOD) boreholes to determine the lithology and deformational textures in the fault zones and host rocks. Cutting samples represent the lithologies from 1.7-km map distance and 3.2-km vertical depth adjacent to the San Andreas Fault. We analyzed two hundred and sixty-six grain-mount thin-sections at an average of 30-m-cuttings sample spacing from the vertical 2.2-km-deep Pilot Hole and the 3.99-km-long Main Hole. We identify Quaternary and Tertiary(?) sedimentary rocks in the upper 700 m of the holes; granitic rocks from 760–1920 m measured depth; arkosic and lithic arenites, interbedded with siltstone sequences, from 1920 to ~3150 m measured depth; and interbedded siltstones, mudstones, and shales from 3150 m to 3987 m measured depth. We also infer the presence of at least five fault zones, which include regions of damage zone and fault core on the basis of percent of cataclasite abundances, presence of deformed grains, and

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presence of alteration phases at 1050, 1600–2000, 2200–2500, 2700–3000, 3050–3350, and 3500 m measured depth in the Main Hole.

These zones are correlated with borehole geophysical signatures that are consistent with the presence of faults. If the deeper zones of cataclasite and alteration intensity connect to the surface trace of the San Andreas Fault, then this fault zone dips 80–85° southwest, and consists of multiple slip surfaces in a damage zone ~250–300 m thick. This interpretation is supported by borehole geophysical studies, which show this area is a region of low seismic velocities, reduced resistivity, and variable porosity.

Introduction

The San Andreas Fault Observatory at Depth (SAFOD) is part of the Earthscope initiative and tests fundamental questions regarding earthquake and fault mechanics (Hickman et al., 2004; http://www.icdp-online.de/sites/sanandreas/index/). In addition to numerous geophysical applications, the project also provides an opportunity to directly sample rocks related to active faults at depth. One of the primary objectives of the SAFOD project is to determine the structure and composition of the San Andreas Fault zone at depths where earthquakes nucleate. A compilation of data collected from 2002 to 2005 in two closely spaced boreholes (~15- m map distance separation) at the SAFOD drill site, near Parkfield, California (Fig. 2-1) provides insight into fault zone properties. These data, along with measurements of in situ stress, permeability and pore pressure conditions, analyses of frictional behavior of fault zone materials, and the determination
of physical properties and chemical processes in the fault zone, will help constrain the behavior of seismogenic and creeping faults.

Much of our understanding of fault zone properties in the upper 2–15 km of the Earth’s crust is largely derived from studies of exhumed faults. The composition and structure of fault zones, along with the deformation mechanisms, the fluid-rock interactions, and evolution of fault zones in the context of the seismic cycle, have been examined in a variety of settings by numerous workers (Anderson et al., 1980, 1983; Caine and Forster, 1999; Chester and Logan, 1986; Chester et al., 1993; Cooper and Norris, 1994; Faulkner et al., 2003; Holdsworth et al., 2001; Kondo et al., 2005; Schulz and Evans, 2000; Stewart et al., 2000; Wibberley and Shimamoto, 2003). These studies, among many others, have revealed a great deal about the across-strike structure of fault zones, with the recognition that faults often include a damage zone, where rocks exhibit a higher than background intensity of fractures, small faults, veins, and evidence for fluid-rock interactions, but in which little slip has occurred. At the boundaries of, or within damage zones, which range in width from meters to tens of meters up to 1 km for large-displacement faults, one or more fault cores (centimeters up to 1 m thick) consisting of ultracataclasite, foliated cataclasite, clay gouge, or breccia are typically present. Within these core zones, extremely narrow slip surfaces (Chester and Chester, 1998; Wibberley and Shimamoto, 2003) may record much of the slip along the fault.

There are at least two caveats in using exhumed fault zones as a proxy for the analysis of in situ processes in seismically active faults: (1) With the exception of pseudotachylytes, no fault-related rock retrieved from exhumed faults can definitively be
shown to be the product of seismic slip, and (2) post-slip alteration, during uplift or while faults are inactive at depth, may alter the textures of fault-related rocks. Observations via drilling into active faults can help to overcome these issues and can tell us much about the deformation processes within faults (Hung et al., 2005; Ikeda, 2001; Matsuda et al., 2001; Moore et al., 1995; Ohtani et al., 2000). Drill hole-based studies provide opportunities to clarify the nature of fault slip at depth and reduce the impact of overprinting, associated with surficial processes, which may obscure the primary textures and geochemical signatures in faults.

The San Andreas Fault Observatory at Depth (SAFOD) project is aimed at examining the processes of fault slip. Unlike previous fault-zone drilling projects, SAFOD provides two unique opportunities: (1) SAFOD targets a section of fault in which earthquakes currently nucleate, rather than in the upper portion of a fault, above the seismogenic region, and (2) SAFOD integrates geological studies and subsurface sampling with geophysical data to help define in detail the processes associated with a slipping fault.

In this contribution, we present the results of quantitative analyses of cuttings obtained during drilling of SAFOD as a significant method for characterizing fault-zone deformation within a seismically active fault zone. Cuttings recovered from the Pilot Hole (PH) drilled in 2002, Phase One (MH1) Main Hole drilled in 2004, and Phase Two (MH2) Main Hole (MH) drilled in 2005 were systematically examined to determine lithology and to document the distribution and style of deformation and alteration within each borehole. Detailed optical microscopic analyses of cuttings samples obtained from
the SAFOD boreholes provide valuable information about the sedimentary and igneous mineral assemblages, textures, alteration products, and deformational features present within individual grains. Thin-section analyses of samples from fault zones allow for quantitative measures of mineral abundance, degree of deformation, and alteration products associated with faulted sequences throughout the boreholes. Identification of the abundance of cataclasite in the cuttings allows for the determination of the relative locations (at the meter-scale range) of damage zone and fault core, and may correlate with previously identified shear zone locations inferred from geophysical logs (Boness and Zoback, 2004, 2006).

We also use X-ray diffraction (XRD) analyses to determine the primary mineral assemblages in several samples. Our work, in combination with other whole-rock geochemical and XRD studies (Kirschner et al., 2005; Solum et al., 2006) and borehole geophysical studies (Boness and Zoback, 2006), provides constraints on the design and coring of the active San Andreas Fault zone (SAF) or Phase Three of SAFOD, planned for the summer of 2007. This work also develops a conceptual model for the geologic setting in which the target earthquakes occur and, in general, may offer insight into broader questions associated with the deformation and structure of fault zones.

The objectives of this paper are to: (1) present the results of analysis of thin-section grain mounts produced from the drill cuttings as a primary method to identify mineral assemblages and differentiate lithologic sequences throughout the PH and MH; (2) observe and describe microstructural deformation features within individual grains; (3) categorize and correlate fault zones by the presence of cataclasite and microfractures
between the PH and MH; (4) discuss the implications of these results for the coring plan in 2007; and (5) evaluate the implications of our work for the study of fault-zone composition, structure, and processes. This work complements other studies, including (1) the XRD analyses of Solum et al. (2006), which describe detailed information regarding mineralogy; (2) the borehole geophysical interpretations illustrating rock properties with depth (Boness and Zoback, 2006); and (3) the geological investigations of rocks present in the region (Draper, 2007).

Geological and Geophysical Setting

The SAFOD drill holes lie 1.8 km southwest of the surface trace of the active strand of the San Andreas Fault, at the northeastern end of the seismogenic Parkfield segment, and adjacent to the creeping segment to the northwest (Fig. 2-1A). At this point along the SAF, the fault experiences 1–2 cm/yr of creep over a zone ~10 m wide at the surface (Murray and Langbein, 2006; Zoback et al., 2005). The SAFOD site lies north of the 1966 Mw 6.0 southeast-propagating Parkfield rupture segment, and is also at the northern edge of the fault segment of the 2004 northwest-directed Mw 5.9 rupture Parkfield earthquake. To the northwest, the SAF has a creep rate of 2.5 (Titus et al., 2005) to 3.9 cm/ year (Argus and Gordon, 2001). Numerous small earthquakes (Mw 0–Mw 2.0) are located in this region at depths as shallow as 2–3 km (Chavarria et al., 2004; Nadeau et al., 2004; Thurber et al., 2004).

Geologically, the site lies in a complex zone of contractional and strike-slip deformation (Fig. 2-1A). The southern Coast Ranges here are composed of a granitic block west of the SAF, interpreted to be Salinian granitic rock, and the Franciscan block
to the northeast (Dickinson, 1966; Page et al., 1998). The Franciscan block is comprised of southeast-plunging anticlinoria cored by serpentine bodies and metasedimentary rocks of the Franciscan Formation and unconformably overlain by unmetamorphosed sedimentary rocks of the Great Valley sequence (Ross, 1978).

Figure 2-1A. Generalized geologic map of the of the SAFOD site, central California. Map compilation sources are: Durham (1974), Sims (1990), Waldron and Gribi (1963), Thayer and Arrowsmith (2005), and Dickinson (1966). BCFZ – Buzzard Canyon Fault Zone; GHF – Gold Hill Fault; TMT – Table Mountain Thrust. Sources of geologic mapping are of different vintages and scales, and the compilation represents our attempt at correlating contacts and rock units.
Geologic mapping of the area indicates that folded and faulted Tertiary through Jurassic rocks are present in surface exposures east of the SAF (Dibblee 1971; Rymer et al., 2003; Sims, 1990). To the southeast of the fault, seismic reflection and refraction studies reveal a step-like feature in the P-wave velocities across the site, with a shallow, high-velocity region likely underlain by Salinian rocks to the southwest, and a low-velocity region to the east of the SAFOD boreholes (Fig. 2-1B; Hole et al., 2006; Thurber et al., 2004; Zhang and Thurber, 2005). Hole et al. (2001, 2006) use seismic data to show
a moderately northeast-dipping transition from high- to low-velocity rocks at the SAFOD site (Fig. 1-1B).

The vertical PH was drilled to a depth of 2.2 km in 2002, and the MH was drilled in two phases in 2004 and 2005. The MH is vertical to a depth of 1500 m, where the hole begins its deviation in a N 35° E bearing, with an ultimate angle of inclination of ~55° at 2070 m measured depth (MD) or 1970 m true vertical depth (TVD) (Fig. 2-1B). This angle was maintained to the bottom of the hole measured at 3067 m TVD or 3987 m MD (Fig. 2-1B).

The PH is 22.25 cm in diameter, and the MH is 31.15 cm diameter to a depth of 3050 m and 20.95 cm from 3050 m to the total depth (TD) of 3987 m. Phase One and Phase Two drilling included direct sampling of 24 m of short cores acquired at 1476, 3056, and at 4028 m MD, and 52 percussive sidewall cores 2.4 cm in diameter by 1–3 cm in length. Thus, the available cuttings represent a continuous and complete sampling over the entire interval of rocks encountered in the borehole.

The boreholes were drilled with a mud-based rotary drilling system using carbide and diamond-tipped, tri-cone drill bits. Drill cuttings are the coarse to fine, sand-sized rock particles created from the cutting action of the drill bit pads and are circulated to the surface via the drilling mud system. Cuttings mixed with bentonite-based drilling mud continuously stream across the shaker table of the drilling rig. Approximately 0.5 kg of cuttings were collected for every 3 m MD, 1 kg collected every 30.48 m MD, and ~3 kg collected every 91.4 m MD along the SAFOD drill holes. More closely spaced cuttings were collected continuously in areas where real-time drilling information, such as
changes in drilling rate or the presence of gas, indicated the presence of zones of geological interest. Near real-time analyses of the on-site washed cuttings performed by commercial mud loggers give a basic lithologic description of the rocks encountered in the boreholes. These analyses focus on macroscopic surface features of the grains, such as color and estimated grain size, and do not include information regarding the intensity or cause of deformation. Also, the mud logging does not allow for quantitative estimates of composition or degree and types of alteration. Other data of interest that give an added context to our work include rate of penetration (ROP) data, which measure the rate of the drill bit advance and provide insight into rock strength at the bit, and near real-time gas analyses.

Methods

The drill cuttings examined in this study were washed in the laboratory in a 140-mesh sieve (~0.1 mm diameter) to remove drilling mud, followed by a magnetic separation of the cuttings on a magnetic plate to remove drill bit fragments from the cuttings. Samples were decanted with distilled water to separate mud additives, which primarily consist of crushed walnut shells. A mechanical riffle-style sample splitter was used to obtain representative samples of the washed cuttings from each depth interval. Each of these samples was then sieved to the 2-mm fraction for further analyses. Thin-section grain mounts were made at ~30.48-m (100-ft) intervals within the PH to a depth of 2164 m, and in the MH from 670 to 3048 m MD. From 3048 m to 3985 m MD, sample spacing ranges from 0.3 to 33 m to capture the variations in composition and texture associated with drilling breaks or lithologic changes interpreted from the mud logs or the
wireline logs. Closely spaced samples (< 3 m) were collected concurrently with drilling on-site by our research group and are not part of the archived SAFOD collection. Nomenclature for drill-hole measurements typically expresses the location along the borehole in MD along the wellbore path. Drilling coordinates in the United States are registered in feet, and we convert all data to the metric system. True vertical depths (TVD) correct the MD values using the borehole deviation survey of the hole.

A total of two hundred and sixty-six thin-section grain mounts from samples in both boreholes were analyzed for mineral assemblages and fault-related textural analysis using a modified Gazzi-Dickinson method (Dickinson, 1970) with individual counts taken incrementally every 0.5 mm on an equally spaced, 300-point grid pattern (Dickinson, 1970). At each individual point, the composition and textural feature were recorded, with the primary subcategories designated for minerals, alteration products, and cataclasite. The individual point counts were recorded as modal percents of the total and were cataloged by measured depth. The recorded abundance of individual minerals, cataclasite, and altered fabrics was plotted as a function of depth, correlating lithology and shear zones to the observed petrology (Fig. 2-2). The categories used to examine the samples were: cataclasite, altered cataclasite, sedimentary lithic fragments, volcanic lithic fragments, mica, calcite, plastically deformed quartz, monocrystalline quartz, plagioclase, sanidine, microcline, altered feldspar, deformed feldspar, opaque grains (interpreted to be oxide minerals), symplectite, chlorite, olivine, and amphiboles. Data files containing the raw data and photos of the thin sections are available in the electronic appendix.
Figure 2-2A. Lithologic sequences and percent abundances of minerals, alteration products, and cataclasite plotted as a function of depth in the pilot drill hole.
Figure 2-2B. Lithologic sequences and percent abundances of minerals, alteration products, and cataclasite plotted as a function of depth in the main drill hole.

X-ray diffraction analysis was performed on thirty samples with an X Pert Pro Diffractometer system running at 45KV/40 Ma with copper tubing. X pert Data Collector and X Pert High Score software were used for data analyses to determine mineral compositions present in the deeper portions of the MH section from 3078 to 3864 m MD.

To simplify the display of results, we summarize and divide the cuttings data into seven main categories: quartz, feldspar, lithic fragments, oxide minerals, cataclasite...
fragments, and total percentages of altered and/or deformed crystal fragments. It is important to note that due to the nature of drilling and mud circulation processes, there are inherent limitations to the geologic interpretation of drill cuttings (Winter et al., 2002). The potential limitations include: (1) mixing of cutting sample may occur as the drilling fluid is circulated along the side of the drill string; (2) samples taken at spaced intervals may not effectively represent sharp transitions observed in some of geophysical borehole or image-log analyses (Boness and Zoback, 2004; Draper et al., 2005) because any sample represents cuttings over some finite interval of rock at the drill-bit tip region; (3) thin-section mounts of drill cuttings represent an extremely small portion of the total sample collected at the SAFOD site; and (4) analysis of grains with optical microscopy does not allow for the characterization of fine-grained rocks in both the protolith and the fault zones (see Schleicher et al., 2006).

Valuable geologic information relating to the subsurface lithology, and distinct mineral assemblages through identified sequences, are obtained from the analysis of thin-sectioned drill cuttings. When merged with other data sets, including detailed X-ray diffraction analysis (Solum et al., 2006), the results from these data enable us to determine the lithology and structure encountered in the borehole (Pechnig et al., 1997; Winter et al., 2002), and to constrain the location of potential areas of interest during the continuous coring program proposed for 2007.

Results

We summarize the lithologies of the rocks cut by the SAFOD Pilot Hole and Main Hole (Figs. 2-2 and 2-3) as seen in the cuttings samples, followed by a discussion of the
alteration and deformation features as a function of depth throughout each hole. We also present microscopic observations of the major rock types, fault and fracture characteristics, and distinct textures, with a brief review of X-ray diffraction data on several samples.

Figure 2-3. Alteration abundances and the summary of the lithologies intersected by the SAFOD MH, and the gamma-ray borehole log, in 1:1 orientation for the deviated main borehole at SAFOD. Locations of faults in inferred from the changes in lithology denoted from the point count data, or from the abundance of altered and cataclastically deformed grains. BCF – Buzzard Canyon fault; SAF – San Andreas Fault.
Lithology

On the basis of the modal content of the cuttings examined, we identify four major lithologies in the SAFOD drill holes: (1) Quaternary and undifferentiated Tertiary sediments; (2) granitic rocks; (3) arkosic sedimentary rocks; and (4) fine- to very fine-grained sedimentary rocks (Figs. 1-2 and 1-3). The Quaternary and Tertiary sediments occur over the interval of 0–760 m. The granitic rocks are subdivided into a granite with a quartz content of 35% to 55% from 760 to ~1450 m MD and a granodiorite (quartz ~20% of total, feldspar, both altered and unaltered, 30%–50% of the total) from ~1450–1920 m MD. We distinguished the granitic rocks above 1450 m from the granodiorite below on the basis of the percentage of quartz grains and the abundance of ferromagnesian minerals, specifically biotite and hornblende. The arkosic rocks include an upper sequence from 1920 to 2550 m MD, separated by a clay-rich zone from 2530 to 2680 m MD, and a finer grained lower sequence from 2680 to ~3150 m MD. The deeper section of the borehole is characterized by a fine-grained, quartz-feldspar-rich siltstone from 3150 to 3550 m MD, and a very fine-grained siltstone to shale from 3550 to 3987 m MD.

The uppermost sedimentary sequence (0–760 m MD) is likely the Pliocene Paso Robles and late Miocene Santa Margarita formations, exposed at the surface and encountered in the subsurface northwest, west, and southwest, of the SAFOD drill site (Dibblee, 1973; Dibblee et al., 1999; Durham, 1974; Graham et al., 1989; Thayer and Arrowsmith, 2005). The sedimentary fragments from these Quaternary/Tertiary deposits are characterized by fine-grained angular to subangular grains composed mainly of quartz
and plagioclase in a very fine-grained matrix. Volcanic lithic fragments are abundant throughout this sequence and commonly have a highly altered, fine-grained to glassy groundmass (Figs. 2-2A, 2-2B). Calcite-rich cements are observed throughout both the PH and MH over this interval.

The granitic rocks encountered below these sedimentary rocks (760–1920 m MD) are likely part of the Mesozoic Salinian Block that lies west of the San Andreas Fault in the region (Dibblee, 1973; James and Mattison, 1988; Ross, 1978). We define an upper granite (quartz 40%–60%, feldspars 20%–40%) from 760 to 1450 m MD (Figs. 2-4A – 2-4C), and a granodiorite between 1450 and 1920 m MD (quartz 20%–40%, feldspars modal values of 40%, 2%–5% Fe-Mg minerals (mostly hornblende), and 4%–6% biotite. Between 80%–95% of the quartz encountered in the cuttings consists of monocry stalline quartz, with a minor fraction of either polycrystalline or plastically deformed quartz (Fig. 2-4B) indicative of metamorphic rocks associated with the Salinian block (Ross, 1978). Good evidence for a fault does occur within the upper granite unit around 1050 m (Figs. 2-2 and 2-3).

The lithologic break at ~1450 m is not associated with a significant increase in alteration or cataclasite abundances (Figs. 2-2 and 2-3); however, the texturally and compositionally abrupt change in lithology, mineralogy, and borehole and geophysical character encountered in the MH at 1920 m MD reflects a change from Salinian granitic rocks to a sedimentary sequence that consists of two types of arkosic to lithic arenites (Draper, 2007; Draper et al., 2005; Solum et al., 2005a, 2006). This sedimentary sequence is characterized by 20%–60% lithic fragments in the samples. The lithic
fragments within this sequence are fine-grained, subangular grains composed primarily of quartz and mafic minerals in a very fine-grained matrix (Figs. 2-4D – 2-4F). Individual grains of highly altered volcanic groundmass were also observed, but overall represented a small portion of the total grains point counted.

A broad, clay-rich zone from 2530 to 2680 m MD (Draper, 2007) divides this sequence into two packages. Differences in lithic abundance and composition, the nature of chloritic grains, and alteration products between the two packages were determined with microscopy of cuttings and core in conjunction with image-log analysis and integration of borehole-based geo-physical logs (Draper, 2007). Based on XRD analyses, the lower package is enriched in chlorite and illite relative to the upper package. The lower package also contains laumontite, which is generally absent in the upper package (Solum et al., 2006). The depositional setting, age, and tectonic implications of this block of arenites are discussed in Draper (2007), who suggests that this package of rocks represents a proximal portion of a submarine fan or turbidite sequence, perhaps part of a Late Cretaceous to Early Tertiary Salinian cover sequence found west of the San Andreas Fault (Clarke and Nilsen, 1973; Draper et al., 2005; Graham et al., 1989; Grove, 1993; Seiders and Cox, 1992).
Figure 2-4. Photomicrographs of lithologies of cuttings from the SAFOD holes. A) Salinian granite grain from 701 m in the PH. Quartz (Q), micas, and feldspar (Fp), and opaques (opq) form an interlocking igneous texture, B) polycrystalline deformed quartz grain (Qp) from 1219 m depth within the upper Salinian granite unit, C) Plagioclase feldspar (Fp), polycrystalline quartz (Qp), and alteration of feldspars (Falt) within Salinian granite, D) Sedimentary fragments from lithic arenite, with volcanic lithic clast (Lv), fine-grained sedimentary lithic clasts (Ls), and quartz (Q) and feldspar grains (Fp), E) Sedimentary lithic-rich fine grained sequence from 2560 m depth, F) Fine-grained sedimentary grains near the base of the arkosic section at 2987 m, G) Fine-grained siltstone (Ls) and very-fine grained altered lithic (Lalt) from 3328 m, H) Very fine-grained siltstone, with ghost grain outlines (red arrow defining bedding, I) Siltstone from 3581 m depth, with fossil indicated by the red arrow, and a possible glaucophane clast, in green, in a fine-grained clayey matrix.
The deepest lithologic change occurs at ~3150 m MD, where the arenites are abruptly replaced by fine-grained siltstone and shale fragments (Figs. 2-2B and 2-4G). Due to the fine-grained textures of these fragments and the binning required by the Gazzi-Dickinson method, many of these grains are classified as lithic clasts (Figs. 2-2B and 2-4H), but, in reality, they are fragments of quartz-rich siltstone to mudstone. At a depth of ~3400 m MD, we lose most of the distinct quartz and feldspar grains in the thin sections, suggesting the rocks from ~3400 to ~3850 m MD are mudstones, some of which contain fossils (Fig. 2-4I). This depth also marks a pronounced change in clay mineralogy because below this depth chlorite concentration and crystallinity are fairly homogeneous (Solum et al., 2006). At the bottom of the hole, the percentage of quartz increases and lithic fragments decrease, suggesting the presence of a siltstone sequence. From 3850 m MD to the end of the drill hole, the gamma-ray log and optical microscopy suggest a mixed lithology of siltstone and claystone.

**Alteration and Deformation**

We use the term *alteration* in this work to denote the presence of minerals such as sericite (fine-grained illite or muscovite), calcite, zeolite minerals, chlorite, and clay minerals that cannot be optically resolved and are often overprinted on pre-existing minerals (Fig. 2-5) or occur as fragments of what appear to be veins. Careful attention was paid to the identification of alteration phases because the heterogeneous quality of the samples collected throughout the borehole may create a bias in recognition. For example, with these samples, it is relatively easy to identify alteration in the granite and granodiorite sequence; however, it proved more difficult within the deeper, fine-grained
sections, where the alteration phases may also be of detrital origin or not readily visible. We identify several zones in which alteration phases (determined on the basis of composition and texture) comprise >20% of the modal amount of grains (Fig. 2-2): (1) an ~150-m wide zone (as sampled in the vertical drill hole) in the MH at ~1050 m; (2) a broad region from 1600 to 2000 m MD; (3) a minor zone with greater variability between 2200 and 2500 m MD in the upper sedimentary section; (4) a section of increasing alteration from 2700 to 3000 m MD; (5) numerous zones between 3050 and 3350 m MD; and (6) a thin zone ~3600 m MD.

Alteration products and textures include sericitization of feldspars and recrystallization of quartz (Figs. 2-5A and 2-5B), calcite replacement mineralization (Fig. 2-5B), calcite veins (Fig. 2-5C), zeolite overprints on host grains (Fig. 2-5D), and the formation of fine-grained clays and/or talc (Fig. 2-5E). Remnants of calcite veins within individual grains may indicate periods of fluid movement in or near fault zones since they are commonly attached to or found layered with cataclasite. Alteration of the Salinian rocks correlates well with the abundance of cataclasite fragments (Fig. 2-2B) indicating that alteration in that section is likely associated with deformation rather than broad alteration of the block.

Significant abundances of deformed and/or cataclasite grains are observed in several locations within the MH 1050, 1650–1750, 1900–2000, ~2650–2700, 3050–3300, and ~3650 m MD (Figs. 2-2 and 2-3). Four main styles of cataclasite deformation are observed in this study: (1) individual grains or zones with intense fracturing and what appears to be the initial stages of grain comminution within intragranular fractures (Fig.
2-6A); (2) relatively unaltered cataclasite (Fig. 2-6B); (3) altered cataclasite (Fig. 2-6C); and (4) layered and highly deformed cataclasite (Fig. 2-6D). The undeformed/unaltered cataclasite is characterized by very fine-grained rounded to sub-rounded grains in a dark-gray or dark-brown, ultrafine groundmass. Cataclasite may also be found sutured to undeformed grains and/or may consist of various layers comprised of comminuted and rotated grains, fine-grained clays or unidentified matrix, iron-oxide/hydroxides, and quartz or calcite veins (Figs. 2-6E – 2-6F). The altered cataclasite is characterized by the presence of very fine-grained rounded feldspar grains to a zeolite phase with indistinct extinction, fibrous or fuzzy habits, and gray-white pleochroism (Fig. 2-6C). The deformed cataclasite is typically foliated and very fine-grained and may occur as a multi-layer sequence including mineralized microfracture surfaces. Feldspars exhibit significant deformation in the regions of high cataclasite content (Figs. 2-6B and 2-6E), with abundant alteration and intra-granular, cleavage-controlled fractures. The amount of feldspar alteration is interpreted to be a possible product of increased fluid migration and/or compartmentalization adjacent to shear-one locations.
Figure 2-5. Photomicrographs of altered grains from SAFOD MH cuttings. A) Feldspar (Fp) and quartz (Qp) fragment cut by microfaults and thin cataclasite zones as indicated by arrows at 1829 m MD, B) Altered granitic fragment at 1676 m MD consisting of calcite (cal), altered feldspar (Falt), C) Highly mineralized calcite grain within a zone of deformation, with textures at right end of grain suggesting it comes from a part of a vein, at 1951 m MD, D) Zeolite (zeo) lining a very fine siltstone fragment at 3668 m MD, possibly laumontite and, E) Predominately fine-grained lithic clast with alteration and development of clay rims (cl/alt).
Figure 2-6. Photomicrographs of deformation microstructures from the SAFOD MH. A) Fractured grains from 1829 m MD showing microfractures as a result of cataclasis within a deformed area slightly above the inferred location of the Buzzard Canyon fault, taken with the gypsum plate inserted, B) Cataclasite fragments from 1920 m MD, within the damage zone of the fault between the Salinian block and the arkosic sedimentary sequence, with thin Fe-oxide alteration at the edge of one of the grains, C) Fine-grained altered fragment from 3582 m MD with calcite-filled fractures, D) Calcite-filled fractures with fine-grained foliated cataclasite in a intensely deformed zone at 3341 m MD, E) Multiple stages of deformation exist showing microfracturing, cataclasis, veining, and alteration all within a single grain at 3499 m MD, F) Very fine-grained siltstone grain with microfault marked by cataclasite and iron-oxide/hydroxides and adjacent calcite-filled fractures at 3598 m MD.
The occurrence of cataclasite in the PH suggests that it encountered a fault zone in the granitic sequence at 1500 m. We infer that this fault zone was intersected in both drill holes at roughly the same depth, which would imply that the fault dips shallowly northeast (Fig. 2-3). This relationship may coincide with the lithologic transition between the granite and granodiorite, the reduced Vp and Vs values, and changes in resistivity seen in the borehole geophysical logs at 1150–1400 m (Boness and Zoback, 2004).

Observations of cataclasite, deformation features, and alteration show a decreasing trend near the bottom of the PH, as compared to an increasing trend in these features at similar depths (~1900–2000 m MD) within the MH. The arkosic-rich sedimentary section that intersects the MH at 1920 m MD is also not documented near the base of the PH. These observations support the presence of a steeply southwest-dipping fault within the MH, which was not yet penetrated by the PH due to the completion depth (Figs. 2-2 and 2-3). The broad distribution of the alteration and cataclasite intensities in the MH data suggests that this fault is a relatively large fault, and it may represent the down-dip continuation of the Buzzard Canyon fault (Hole et al., 2006; Rymer et al., 2003; Thayer and Arrowsmith, 2006). Deeper in the section, the presence of another broad region of intense deformation and cataclasite combined with alteration between 3000 and 3300 m MD may represent a major strand of the San Andreas Fault and surrounding damage zone, with the abundance of cataclasite noticeably decreasing below 3600 m MD in the MH.

The intensity of alteration correlates reasonably well with cataclasite abundances measured throughout the hole (Figs. 2-2 and 2-7). A region of such correlation deep in the hole, and which may have a bearing on the SAF sensu stricto, is the zone of increased
alteration and cataclasite abundance observed in the 3050- to 3350-m MD interval (Fig. 2-2). Alteration phases identified through microscopic analysis of the cuttings include quartz, calcite, chlorite, sericite, iron oxides, serpentine, zeolites, and clays. X-ray diffraction analyses of Solum et al. (2006) document bulk compositions, relative mineral abundances, and details of clay mineralogy of this interval and throughout the entire MH. This region also correlates with increases in ROP observed at 3185–3215 and 3290–3353 m MD, both of which are also associated with changes in mud-gas composition (gas interpreted to be exsolved from the formation; Wiersberg and Erzinger, 2005).

As a supplement to the microscopic identification of minerals, we used X-ray diffraction analysis to further examine the potential constituents of the cutting samples from the region of 3078–3864 m MD (Table 2-1). Minerals denoted in this table have at least 5%–10% relative abundance in each sample. Note that sample material from 3520 m MD and deeper was extremely limited and resulted in weak signatures; therefore, only the identification of primary peak phases was possible. We identify several rock types based on mineralogy.
Almost all samples have quartz and feldspar. Samples to a depth of 3325 m MD are relatively clay poor, contain muscovite, and have Mg-Fe-Al oxides and a scant amount of zeolites. From 3335 to 3356 m MD, the rocks contain illite and kaolinite, and, in several cases, halite, along with Mg and Fe oxides. The deepest section of the hole recovered olivine, zeolites, Ti-oxides, cristobolite or trydimite, ± minor sulfides. The presence of oxide phases and clay minerals indicates three zones of increased alteration: 3078–3290; 3330–3345, and 3520–3595 m MD.
Discussion

Our analysis of drill cuttings from the SAFOD boreholes provides a preliminary view of the details of the lithology, alteration, and nature of deformation in the rocks encountered in the SAFOD boreholes. This work reveals aspects of the structure and composition of the volume of rock surrounding the SAF, and can be used as a guide for further studies of the fault zone continuing at the SAFOD site.

Lithology, Geologic Setting, and Tectonics

A detailed discussion and synthesis of the geologic and tectonic interpretation of the rocks encountered in the SAFOD boreholes are beyond the scope of this paper because such an analysis requires the synthesis of the data presented here and many other data sets, including, but not limited to: Sims (1990); Thurber et al. (2003, 2004); Rymer et al. (2003); Unsworth and Bedrosian (2004); McPhee et al. (2004); Hole et al. (2001, 2006); Thayer and Arrowsmith, (2005); Boness and Zoback (2006); Solum et al. (2006); and Tembe et al. (2006). We focus here on the rocks encountered by the borehole and their implications for coring in 2007.
Table 2-1. Bulk X-Ray diffraction results for samples from 3078 to 3864 m MD in the SAFOD main hole.

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<th>Pyroxenes</th>
<th>Clay minerals*</th>
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● indicates a primary mineral constituent (>50%)
○ indicates a secondary constituent (20 – 50%)
□ indicates a trace constituent (<20%)
*Clay minerals: k = kaolinite; i = illite; i/m=illite/montmorillonite
** analyses has low confidence as sample material was limited and heavy metals from drilling material were present.
We define four major lithologies in the borehole and suggest that at least five major faults were encountered (Figs. 2-3 and 2-8). Lithologic analysis of the cuttings supports the interpretation of borehole geophysical data acquired in the two holes (Boness and Zoback, 2004, 2006), which suggested the presence of seven distinct lithologic changes in the area. Most of the faults appear to be steeply southwest-dipping faults, as suggested from seismic imaging of the region (Hole et al., 2001, 2006), and the location of microseismicity (Thurber et al., 2004). When correlated with borehole geophysical data (Boness and Zoback, 2006; Zoback et al., 2005), the active strand of the SAF, inferred from the location of wellbore casing deformation, location of small earthquakes, and the presence of a low-velocity zone (Zoback et al., 2005), appears to be associated with a region of significant alteration (Figs. 2-2, 2-3, and 2-8) at 3300–3500 m MD. Our analysis of the cuttings documents the presence of the arkose and lithic arenites between the vertical portion of the drill hole and the San Andreas Fault. We also suggest that while a fine-grained lithology is encountered below the arenites, this contact does not correspond to the active strand of the SAF. The lithologies encountered deep within the borehole consist of well-indurated siltstones and mudstones that are part of the uppermost Great Valley sequence based on analysis of microfossils (K. McDougall, written commun., 2006), and the presence of volcanic quartz and olivine detrital grains as determined from the X-ray diffraction analyses. Thus, any subsurface geologic model of the site needs to incorporate the presence of a high-velocity arkosic sedimentary section southwest of the fault and the fine-grained lithologies north-east of the fault that are not consistent with the Jurassic Franciscan Formation (Hole et al., 2001, 2006). An added
structural complexity introduced by the presence of the Great Valley sequence at the bottom of the SAFOD MH is that Franciscan rocks are exposed at the surface ~3 km northeast of the SAF (Fig. 2-1A). Thus, the internal geometry of the SAF and its related structures appear to be more complex than originally interpreted from geophysical data and surface mapping (Dibblee, 1971; Hole et al., 2001; McPhee et al., 2004; Page et al., 1998; Sims, 1990; Unsworth and Bedrosian, 2004).

Figure 2-8. Borehole geophysical data plotted on the approximate orientation of the borehole, from 3100 m MD to the end of the hole, with alteration and cataclasite abundances plotted. Borehole geophysical data provided by M. D. Zoback. The location of the borehole casing deformation is shown, and regions where our data suggest the presence of a fault indicated in yellow. Shading indicates lithologies determined from cuttings analysis.
The steep change in the resistivity structure of Unsworth et al. (2003) and Unsworth and Bedrosian (2004) appears to correspond to the presence of a well-developed fault at the Salinian-arkosic sequence transition in the borehole and may correspond to the Buzzard Canyon fault zone mapped at the surface (Figs. 2-1A and 2-9; Rymer et al., 2003; Thayer and Arrowsmith, 2005). Increased alteration and deformation between 3300 and 3500 m MD may correspond to the SAF, which would indicate the fault dips 80–85° southwest and consists of several strands at depth. The steep westerly dip agrees with the fine-scale analysis of the earthquakes (Ellsworth et al., 2005; Thurber et al., 2004; Zhang and Thurber, 2005).

The subsurface sections in Figure 2-9 incorporate surface geologic mapping (Sims, 1990; Thayer and Arrowsmith, 2006) and subsurface geophysical data (Catchings and Rymer, 2002; Chavarria et al., 2004; Hole et al., 2001, 2006; McPhee et al., 2004; Thurber et al., 2004). At least two possible interpretations for the subsurface structure are considered after review of the previously mentioned studies and recent work (Boness and Zoback, 2006; Draper, 2007; Evans et al., 2005; Solum et al., 2006; Tembe et al., 2006). The sections shown in this study are permissible, but they are by no means the only interpretations, especially within the deeper portions of the sections where the data are not well constrained.

Common to both interpretations are the following elements: (1) the surface trace of the Buzzard Canyon fault projects down dip and connects to the fault that juxtaposes granodiorite on the southwest side and Tertiary arkosic rocks on the northeast side; (2) the reverse faults in the Tertiary rocks (Thayer and Arrowsmith, 2006) represent small
displacement faults; and (3) the main trace of the San Andreas Fault projects down dip at \(\sim 83^\circ\) and is intersected by the borehole as shown.

Interpretations of the sections differ at depth based on how we interpret the presence of the upper Great Valley sequence at the bottom of the SAFOD hole. In Figure 2-9A, we show the Great Valley sequence and younger rocks as a fault-bounded wedge with the northeastern-most fault being a subsidiary to the San Andreas Fault, as mapped at the surface at the latitude of the SAFOD project (Hole et al., 2001, 2006; M. Rymer, 2005, personal comm.). Adding to the complexity of this interpretation is the presence of the Gold Hill fault (Sims, 1990) directly to the south of the area. Sims (1990) interprets the Gold Hill fault as a steep, northeast-directed reverse fault that is cut off by the San Andreas Fault. In Figures 2-9A and 2-9B, we show the northeast strand to be the northern continuation of the Gold Hill fault, as interpreted by Hole et al. (2001, 2006) and the down-dip projection of the Buzzard Canyon fault, which may merge with the San Andreas Fault at depths greater than 5 km based on fault-zone trapped, wave studies (Shalev and Malin, 2005).
Figure 2-9. Cross sections through the SAFOD drill site region along a line trending N. 35° E. Constraints include the surface geology compiled in Fig. 2-1, analysis of the cuttings discussed in the text, and the subsurface data from McPhee et al. (2004); Chavarria et al., (2004); Hole et al. (2001, 2006); Thurber et al. (2003); and Catchings et al. (2002). A) Cross section interpretation in which the San Andreas fault is interpreted as a fault zone bounded on the southwest side by the active trace, and on the northeast side by a fault seen in mapping (see Fig. 2-1) and projected down dip. This northeast fault may intersect with, or be the same fault as the Gold Hill fault to the southeast. Fault geometry and geometry at depth is not well constrained. In this model, fault geometries are shown to coincide with presence of microseismicity. Small X symbols represent location of earthquakes located within 1 km on either side of the section line from 2000 to 2006, provided by C. Thurber. SAFOD MH total measured depth (TD) lies in the lower portion of a fault-bounded wedge of Great Valley sequence rocks. B) Same section as in A, showing the location of events used by Chavarria et al. (2004), to infer fault structure. C) Cross section with the northeastern fault interpreted to be a cutoff pre-existing fault as shown in Sims, 1990. The presence of Great Valley rocks at the SAFOD MH TD requires another fault between the Great Valley and Franciscan rocks, which might be the result of serpentine diapirism observed in the region. Lower structure of the arkosic rocks southwest of the SAF drawn to show a slightly different form of the arkose/Salinian block.
In an alternate interpretation (Fig. 2-9C), we show the Gold Hill fault as Sims (1990) had interpreted it—cut off by the San Andreas Fault. To explain the presence of the Great Valley sequence encountered in the bottom of the SAFOD borehole, a fault is required between the Great Valley and Franciscan rocks. The steep dip of the contact and the omission of much of the thickness of the Great Valley could be due to diapiric structure within the Franciscan, in which upward flow of the Jurassic rocks placed it against, and just to the northeast, of the Great Valley sequence (see Dickinson, 1966, for nearby field examples).

**Fault Zone Composition, Alteration, and Mechanisms**

Small amounts of whole-rock core samples recovered from 1476 to 1484, 3056 to 3067, and 3150 to 3410 m MD provide information on depositional features, deformation history, and rock properties in the MH (Almeida et al., 2005; Draper, 2007; Schleicher et al., 2006; Tembe et al., 2006). Almeida et al. (2005) show that the upper cored interval from Phase One (1476–1484 m) consists of a medium-grained hornblende biotite granodiorite with leucocratic phenocrysts and weakly foliated lenses. Evidence for both low- and high-temperature deformation is present in the core, including a series of sub-vertical fractures and moderately dipping shears with secondary mineralization comprising centimeter-thick halos of low-grade alteration and staining of host. Abundant fracture sets with irregular cataclastic bands, up to 2 cm thick, are orientated at high angles to the core, recording multiple stages of deformation and fluid infiltration (Almeida et al., 2005).
The core from 3056 to 3067 m MD likewise agrees with the cuttings analysis consisting of a coarse, arkosic sandstone to pebble conglomerate with lithic fragments of granitic, sandstone, siltstone, and volcanic clasts. A clay-rich shear zone several centimeters thick was cored at the bottom of this interval, and Solum et al. (2006) suggest this shear zone could be the southwestern active strand of the SAF (Zoback et al., 2005).

The composition of the whole-rock core from the bottom of the Phase Two drilling (depth of 4028–4036 m MD) agrees with the cuttings data obtained from this depth. The core is composed of shale with several thin beds of siltstone and very fine-grained sandstone, graded bedding, fossil fragments, and bioturbated sections. Numerous small veins, scaly fabric, and polished slip surfaces are observed in the core.

The comparison of the results of our work with the borehole geophysical data (Fig. 2-8) can be used to define a relationship between the physical rock properties and geophysical signatures. Zoback et al. (2005) and Boness and Zoback (2006) indicate that the zone from 3150 to 3410 m MD is characterized as a low-velocity zone, with low gamma-ray and resistivity character, with a small zone at 3295–3313 m MD where the borehole casing is actively deforming due to creep on an active strand of the SAF. Our data suggest that a fault may occur at ~3050 m MD (corresponding to the cored fault at 3066 m), followed by a zone of significant alteration to ~3320 m MD, where we see an increase in the amount of cataclasite in the cuttings (Fig. 2-8) and a decrease in alteration mineral abundances. Other faults may exist between 3500 and 3660 m, where an increase in alteration and cataclasite abundance is associated with changes in standard and neutron porosity and Vp and Vs in the geophysical logs (Fig. 2-8).
Our interpretation of the cuttings can also be examined in light of previous work on fault-zone composition, deformation, and structure from exhumed fault zones (Chester and Chester, 1998; Chester and Logan, 1986; Chester et al., 1993; Faulkner et al., 2003; Wibberley and Shimamoto, 2003) and applied to the understanding of the SAF at depth. The data support the presence of several fault zones characterized by brittle to semi-brittle deformation textures within grains and increased amounts (relative to adjacent samples) of microfractures, fine-grained clays, alteration phases, and zeolite minerals. These zones of deformation appear to be meters to tens of meters wide, and may actually represent damage zones surrounding narrow fault zones consisting of compacted cataclasite, ultracataclasite, and/or fine-grained gouge that may not be resolved based on cuttings analyses alone.

Heterogeneous damage-zone elements are observed at the micrometer scale throughout the borehole and may provide insight into the various styles of deformation and related mechanisms at the meter to tens of meters scale. The character of cataclasite varies within cutting samples as a function of lithology and structural setting. For example, fracture surfaces may vary from a single, discrete, slip surface marked by a coating of clay or iron oxides and/or hydroxides to a complex fracture array consisting of multiple anastomosing fracture surfaces, alternating with coarser cataclasite, veins of polycrystalline quartz filling, and/or calcite alteration. The degree of hydrous phase alteration (e.g., zeolites) and mineralization also suggests that significant amounts of fluid-rock interaction occurred at some point in the history of fault and damage-zone development.
Alteration phases are associated with several of the major fault zones penetrated during drilling. Solum et al. (2006) quantify the mineral assemblages of five major faults penetrated during drilling of the SAFOD MH. As with the results of this study, those faults have highly variable mineral assemblages. A fault within the granitic sequence and a fault separating that sequence from underlying sediments contain the zeolite mineral laumontite, although that phase is present in trace concentrations in other faults. Two faults (one separating the upper and lower arkosic sequence and one at the bottom of the deeper Phase One core) contain a neoformed, mixed-layer, illite-smectite phase. These smectitic clays occur as films (Schleicher et al., 2006), and may be important for determining the mechanical properties of the fault zones that contain these phases. Laumontite is often associated with temperatures of 120–180 °C (Cho et al., 1987; Liou, 1971). The heating required to produce laumontite may be associated with the burial history of the rocks southwest of the SAF (Blythe et al., 2005), or related to hydrothermal alteration associated with faulting. The bottom hole temperature was measured after drilling at 105 °C (http://www.icdp-online.de/contenido/icdp/front_content.php?idart=1033), and Draper (2007) incorporates apatite fission-track thermochronology (Blythe et al., 2005) and new zircon fission-track analysis to constrain the maximum temperature that the arkosic rocks experienced to 240 °C. The deformed and altered rocks observed in the borehole, southwest of the interpreted active strand of the San Andreas Fault, were in the temperature range for plastic deformation of calcite and semi-plastic and brittle deformation of quartz, and in an alteration window associated with clay-zeolite-chlorite
alteration. The exhumation history of the area (Blythe et al., 2005; Draper, 2007) indicates general uplift and cooling from these maximum temperatures, consistent with the nature of alteration observed in this study.

**Implications for Further Work**

The final phase of sampling is to acquire core across the active portion of the seismogenic part of the SAF at depth (see http://www.icdp-online.de/contenido/icdp/front_content.php). This sampling will be followed by installation of borehole seismometers to observe the SAF at depth. Based on the work presented in this paper, the borehole geophysical data sets, and location of earthquakes (Ellsworth et al., 2005), the likely target for coring in 2007 is the region between 3050 and 3450 m MD where the currently active part of the San Andreas Fault is in a fine-grained sedimentary sequence. The general target areas are (1) the low-velocity zone (Boness and Zoback, 2006; Zoback et al., 2005), where the borehole appears to be actively deforming at 3295–3313 m MD (Hickman et al., 2005; Zoback et al., 2005); (2) near where one or more Mw 0 earthquake(s) have occurred (Ellsworth et al., 2005; W. Ellsworth, 2007, personal commun.); (3) where we document a broad zone of alteration with one or more regions of increased abundance of cataclasite; and (4) where microstructures from sidewall core suggest significant deformation (Evans et al., 2005).

The best analogs for the SAF at SAFOD are faults in fine-grained sedimentary rocks, but because of their poor preservation potential, relatively few strike-slip analogs exist. Most studies of exhumed faults in fine-grained rocks are from a variety of tectonic settings (Faulkner et al., 2003; Heermance et al., 2003; Kondo et al., 2005; Solum et al.,
2003, 2005b; Vrolijk and van der Pluijm, 1999; Warr and Cox, 2001; Wibberley and Shimamoto, 2003; Yan et al., 2001) or from faults sampled by drilling (Hung et al., 2005; Moore et al., 1995). Faulkner et al. (2003) draw on geophysical data from the Parkfield area to suggest the overall structure and composition of the Carboneras fault is analogous to the SAF. The Carboneras fault has an estimated strike-slip offset of 40 km, and cuts a wide range of rock types, including crystalline rocks, phyllosilicate-bearing metamorphic rocks, and Tertiary sedimentary rocks. The fault zone is up to 1 km wide, with a broad damage zone interspersed with narrow, anastomosing, clay-rich, gouge zones and very localized, clay-rich, slip surfaces (Faulkner et al., 2003).

Most detailed studies of fault-zone structure and composition in phyllosilicate-bearing gouge and foliated cataclasite indicate that slip occurs along millimeter-thick surfaces, on which neomineralized clay grains grow (Schleicher et al., 2006). Deformation mechanisms consist of slip or glide along cleavage surfaces. Clay-forming reactions may suggest several processes: a significant number of fluid-rock interactions have occurred (Evans, 1988; Vrolijk and van der Pluijm, 1999); anisotropy of permeability may develop (Evans et al., 1997; Morrow et al., 1984); and significant variation in spatial and temporal pore-fluid pressures, mechanical properties, and textures should be anticipated at depth (Chester et al., 2005; Faulkner and Rutter, 2003; Faulkner et al., 2003; Warr and Cox, 2001; Wibberley, 2002).

The data presented in this paper, along with analyses of field analogs and experimental data on permeability, porosity, and mechanical properties of fault-related rocks in fine-grained sedimentary rocks, suggest that the coring effort for SAFOD in
2007 may encounter a range of fine-grained, fault-related material, including brecciated, fractured, and vein-bearing, damage-zone rocks, in which narrow slip surfaces and mineralization and alteration products are common. Pore-fluid pressures may be variable, and recovery of portions of the core may be difficult due to the nature of damage and high degree of fragmentation within the rock. Defining the main slip surface and differentiating between creeping and seismically slipping faults may be challenging and may require careful observations of the cored material coupled with analysis of borehole data. Additional complexity may result from the variability in Vp and Vs values for the faulted rocks, which could make locating the target earthquakes difficult when using short, source-receiver distances.

Conclusions

We integrate results from point counts and microstructural analyses of thin sections from cuttings samples with interdisciplinary research from the SAFOD site to delineate the lithological and structural setting in the subsurface at this location. Four major lithologic packages are identified: (1) Quaternary and Tertiary sediments (0–760 m MD); (2) granitic rocks (760–1920 m MD); (3) arkosic to lithic arenites (1920–3150 m MD) separated by a clay-rich zone (2530–2680 m MD); and (4) fine-grained to very fine-grained interbedded siltstones, mudstones, and shales (3150–3987 m MD). Fault zones are associated with abundances of cataclasite and various alteration products, and are located at similar depths as inferred from borehole geophysical data, including density- or porosity-based logs. The point-count percentage of cataclasite and microstructural deformation features are used to locate several fault strands and related
damage zones within the MH at 1050, 1650–1750, 1900–2000, ~2650–2700, 3050–3300, and ~3650 m MD. The currently active portion of the San Andreas Fault, where the borehole intersects the fault at 3300 m, consists of fine-grained cataclastically deformed rocks with significant alteration and the presence of very narrow, clay-lined, slip surfaces at the micrometer scale.

Zones of alteration occur at 1050, 1600–2000, 2200–2500, 2700–3000, 3050–3350, and 3600 m MD. Overall, alteration is easier to identify in the granitic sequence and occurs within several of the fault zones. Compositional variations and increases in the amount of alteration vary between fault zones and may be indicative of fluid compartmentalization related to the sub-surface lithological and structural architecture.

This work also develops a conceptual model for the geologic setting in which the target earthquakes occur and, in general, may offer insight into broader questions associated with the deformation and structure of fault zones and may be used to provide constraints on the design and coring of the active San Andreas Fault zone or Phase Three of SAFOD, planned for the summer of 2007.

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CHAPTER 3
LITHOLOGY AND INTERNAL STRUCTURE OF THE SAN ANDREAS FAULT AT DEPTH BASED ON CHARACTERIZATION OF PHASE 3 WHOLE-ROCK CORE IN THE SAN ANDREAS FAULT OBSERVATORY AT DEPTH (SAFOD) BOREHOLE²

Abstract

We characterize the lithology and structure of the spot core obtained in 2007 during Phase 3 drilling of the San Andreas Fault Observatory at Depth (SAFOD) in order to determine the composition, structure, and deformation processes of the fault zone at 3 km depth where creep and microseismicity occur. A total of approximately 41 m of spot core was taken from three separate sections of the borehole; the core samples consist of fractured arkosic sandstones and shale west of the SAF zone (Pacific Plate) and sheared fine-grained sedimentary rocks, ultrafine black fault-related rocks, and phyllosilicate-rich fault gouge within the fault zone (North American Plate). The fault zone at SAFOD consists of a broad zone of variably damaged rock containing localized zones of highly concentrated shear that often juxtapose distinct protoliths. Two zones of serpentinite-bearing clay gouge, each meters-thick, occur at the two locations of aseismic creep identified in the borehole on the basis of casing deformation. The gouge primarily is comprised of Mg-rich clays, serpentine (lizardite ± chrysotile) with notable increases in

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magnetite, and Ni-Cr-oxides/hydroxides relative to the surrounding host rock. The rocks surrounding the two creeping gouge zones display a range of deformation including fractured protolith, block-in-matrix, and foliated cataclasite structure. The blocks and clasts predominately consist of sandstone and siltstone embedded in a clay-rich matrix that displays a penetrative scaly fabric. Mineral alteration, veins and fracture-surface coatings are present throughout the core, and reflect a long history of syn-deformation, fluid-rock reaction that contributes to the low-strength and creep in the meters-thick gouge zones.

Introduction

The composition, texture, and internal structure of fault zones reveal how slip is accommodated during faulting and reflect the potential role of fluids during fault zone evolution (e.g. Caine et al., 1996; Chester and Logan, 1986; Chester et al., 1993; Evans, 1990; Evans and Chester, 1995; Evans et al., 1997; Faulkner et al., 2003; Knipe, 1993; Vrolijk and van der Pluijm, 1999; Wibberley et al., 2008). Though much of our understanding of active faulting in the continental crust is derived from examination of inactive, exhumed faults, it is clear that the composition and structure of these rocks may be modified during uplift and exhumation. Therefore to clarify fault structure and the physical and chemical processes of deformation at depth, it is critical to compare the results of the surface studies to research on samples obtained by drilling into active, large-displacement fault zones (Hickman et al., 2004; Ohtani et al., 2000; Reches and Ito, 2007; Tobin et al., 2007). Defining fault zone characteristics using core recovered by drilling is challenging because of the limited sample size, poor core retrieval, and
potentially complex subsurface geology, especially in large displacement faults. Core-based studies, however, reduce the impact of exhumation-related overprinting that can obscure fault-related rock textures and geochemical signatures, and help reduce the uncertainty associated with using exhumed fault zones as a proxy for the analysis of in situ processes and mechanical behavior of active faults (e.g., Isaacs et al., 2007; Ohtani et al., 2000).

The San Andreas Fault Observatory at Depth (SAFOD) borehole near Parkfield, CA (Fig. 3-1) transects the San Andreas Fault (SAF) at approximately 3 km depth where aseismic creep occurs just 10's to 100's of meters up-dip from a region of persistent micro-earthquake activity (Ellsworth et al., 2005; Hickman et al., 2004, 2007; Thurber et al., 2004, 2006; Zoback et al., 2010). Numerous workers have hypothesized that the aseismic creeping behavior and low strength of the SAF in this region are related to the presence of key minerals and specific fluid-rock reaction processes (e.g. Allen, 1968; Carpenter et al., 2009, 2011; Hickman et al., 2004; Holdsworth et al., 2011; Irwin and Barnes, 1975; Janssen et al., 2010, 2011; Lockner et al., 201; Mittempergher et al., 2011; Moore and Rymer, 2007; Moore et al., 1996; Schleicher et al., 2006, 2009, 2010; Scholz, 2002; Solum et al., 2006; Tembe et al., 2006, 2009; Wallace, 19901). In this paper, we add to the existing data set by systematically describing the rock units captured by coring and providing petrographic and geochemical analyses of 30 whole-rock samples to help constrain deformation processes and fluid-rock reactions within the near-fault environment.
Geologic Setting

The SAFOD borehole is in the central California Coast Ranges southwest of the surface trace of the SAF and north of the town of Parkfield, CA (Fig. 3-1A). This area lies within a transitional zone between the central creeping segment and the segments of the SAF that produce great earthquakes (Allen, 1968; Hickman et al., 2004; Rymer et al., 2006; Unsworth et al., 1997). Direct measurements indicate the fault creeps 2 to 3 cm/yr (Titus et al., 2005; 2006) with most deformation concentrated in a 10-m wide zone at the surface (Hickman et al., 2004). Aseismic creep and microseismicity at SAFOD occurs between 2.5 to 12 km depth (Thurber et al., 2006). Historical ruptures on the Parkfield segment, with $M_w$ of approximately 6.0, including the $M_w$ 6.0 earthquake in 2004, have occurred approximately 10 km south of the SAFOD location (Fig. 3-1; Harris and Arrowsmith, 2006).

Rocks exposed east of the SAF near SAFOD include folded and faulted Tertiary through Jurassic siliciclastic rocks, mélange of the Jurassic Franciscan Formation, and sheared serpentinite (Bailey et al., 1964; Dibblee, 1971; Dickinson, 1966; Page et al., 1998; Rymer et al., 2003; Sims, 1990; Thayer and Arrowsmith, 2006). Tertiary sedimentary rocks and Mesozoic Salinian granitoids are exposed to the west of the drill site (Dibblee, 1971; Sims, 1990).
Figure 3-1. SAFOD study area information: A) Location of SAFOD site in central California. The central creeping segment of the San Andreas Fault (SAF) is highlighted in gray with the locked portions of the fault shown in red. Locations of large historical ruptures including the 2004 and 1966 M 6.0 Parkfield earthquakes near SAFOD; B) Borehole geometry (not to scale) and lithologic summary for the SAFOD main borehole and the inferred locations of the Buzzard Canyon Fault (BCF) and the SAF based on cuttings analyses (Bradbury et al., 2007); C) Approximate locations of the 2007 Phase 3 cores relative to the SAFOD main borehole (modified after Hickman et al., 2005; Zoback et al., 2010). The origin represents the position of the SAFOD borehole with the distance to the east in meters shown on the x-axis. The position in meters measured depth (m MD) of the two regions of casing deformation associated with actively slipping segments of the SAF are marked as the Southwest Deforming Zone (SDZ) and the Central Deforming Zone (CDZ) following Zoback et al. (2010). The shaded region in red represents the extent of a fault-related damage zone based on geophysical data with approximate locations of microseismicity shown in the stippled red areas and faults indicated by dashed red lines (Zoback et al.; 2010); D) The extent of the low velocity zone (LVZ) determined from borehole geophysical logs (after Jeppson et al., 2010) between ~ 3-4 km MD. A dashed red-line highlights this measured shift to lower seismic velocities and the position of this feature relative to the inferred active plate boundary (Bradbury et al., 2007; Holdsworth et al., 2011), the SDZ, and the CDZ (after Zoback et al., 2010).
Figure 3-2: Schematic summary of SAFOD Phase 3 core lithology and deformation (not to scale). Sample locations and lithologic information are displayed relative to each coring run and represent an integration of our results described in Tables A-1 – A-3. Listed core depths are in meters measured depth (m MD) based on values measured during drilling and reported in the Phase 3 Core Photo Atlas (www.earthscope.org/safod). Refer to the Supplementary Material in Zoback et al. (2010) for details concerning depth correlation methods for comparing core features to the borehole geophysical log data.

The rocks associated with casing deformation and the SDZ and CDZ are highlighted in red with a dashed red line along the outer core indicating the corresponding region of low velocity or damage zone of Zoback et al. (2010). Drilling mud gas-rich zones (Wiersberg and Erzinger, 2008) are denoted with a black line along the outer core.
Prior to SAFOD drilling, geophysical studies attributed a shallow, high P-wave velocity region southwest of the SAF to Salinian granitoids and a distinct low-velocity region northeast of the SAF to the Franciscan Formation (Hole et al., 2006; McPhee et al., 2004; Thurber et al., 2004; Unsworth and Bedrosian, 2004; Unsworth et al., 1997; Zhang and Thurber, 2005).

SAFOD Borehole and Sampling

The SAFOD borehole was drilled approximately 1.8 km west of the surface trace of the SAF on the Pacific Plate and extends vertically downward to approximately 1.5 km, then is deviated at an angle of approximately 55° from vertical and trends northeastward (Fig. 3-1B). Herein we report depths along the borehole in meters measured depth (m MD) to represent the distance below the drill rig floor (http://www.earthscope.org/data/safod). The borehole crosses the active SAF and penetrates the North American Plate reaching a total measured depth of 3.9 km (Hickman et al., 2007). Borehole observations indicate that the nearest earthquake clusters are located within 100 m, and are directly below the borehole trajectory (Fig. 3-1C; Zoback et al., 2010). The location and distribution of earthquakes over the broader region is characterized by a complex pattern of seismicity consistent with the presence of multiple active slip surfaces in the shallow crust at SAFOD (Thurber et al., 2010).

Bradbury et al. (2007) identified the presence of Salinian granitic rocks in the SAFOD borehole based on cuttings retrieved during Phase 1 drilling between 760 and 1920 m MD. A deformed fault-bounded block of Paleocene-Eocene arkosic sedimentary rocks is juxtaposed with the eastern side of the Salinian block along the Buzzard Canyon
fault (BCF) and extends eastward to the SAF zone (Fig. 3-1B; Hole et al., 2006; Springer et al., 2009). Geophysical data, and cuttings composed of abundant fragments of cataclasite, calcite veins, fine-grained sheared lithics, and flakes of serpentinite, suggest that this block is cut by multiple faults between 1920 and 3300 m MD. Juxtaposition of granite and sedimentary rocks is consistent with significant slip on the BCF, and Springer et al. (2009) suggest that the fault strands within the fault-bounded block also may have accommodated considerable displacement. Farther downhole, on the northeast side of the SAF, well-indurated siltstones and mudstones of the uppermost Cretaceous Great Valley sequence were identified in cuttings and Phase 2 spot core recovered from the easternmost end of the borehole (Bradbury et al., 2007; Pares et al., 2008; Springer et al., 2009).

Sidetrack drilling off of the main hole during Phase 3 intersected the SAF zone at a relatively high angle (Fig. 3-1C). From the sidetrack holes, approximately 41 m of 10 cm diameter, whole-rock core was successfully retrieved (Figs. 3-1 – 3-2) from three continuous intervals between 3141.4 and 3312.7 m MD. The intervals are referenced by hole and core run, i.e., Runs 1-3 in Hole E, Runs 1-3 in Hole G, and Runs 4-6 in Hole G. The Phase 3 core was cut at the drill site into sections 15 to 90 cm long. The depths of specific features captured in the Phase 3 core are slightly different than the depths of correlative features determined from the geophysical logs taken in the main hole (refer to Zoback et al., 2010 for detailed discussion).

A zone of low seismic velocity (LVZ, Fig. 3-1C) was identified from the geophysical logs of the main borehole drilled in Phase 2. The interval between 3192 and
3413 m MD displays $V_p$ and $V_s$ values that are 10 to 30% lower than those for rocks to the east and west (Fig. 3-1D). This zone has relatively high porosity and is cut by multiple slip planes (Boness and Zoback, 2006; Jeppson et al., 2010; Li and Malin, 2008; Li et al., 2004; Zoback et al., 2010). Zoback et al. (2010) interpret this 200-m wide zone of reduced seismic velocity and resistivity as a fault-related damage zone of the currently active SAF. Deformation within the granitic rocks and arkosic sandstones west of the SAF suggest a thicker overall damage zone that reflects multiple episodes of movement along relict and active faults (Chester et al., 2010). Pronounced casing deformation, caused by fault creep, occurs at two localities that are characterized by anomalously low $V_p$, $V_s$, and resistivity, and low total natural gamma signatures. The two regions of fault creep are referred to as the Southwest Deforming Zone (SDZ), located at 3192 m MD, and the Central Deforming Zone (CDZ), located at 3302 m MD (Fig. 3-1D; Zoback et al., 2010). The SDZ and CDZ were successfully sampled during Phase 3 by coring Runs 1-3 in Hole G and coring Runs 4-6 in Hole G, respectively. Coring runs 1-3 in Hole E targeted an inferred structural boundary between sedimentary rocks of Salinian and Great Valley affinity on the west and east, respectively.

**SAFOD Phase 3 Core Characterization**

Lithology, composition, and mesoscale structural features of Phase 3 core are summarized here (Appendix A1 Table A1; Fig. 3-2) on the basis of descriptions made at the drill site during drilling (by J. Chester, F. Chester, D. Kirschner), at the U.S.G.S in Menlo Park, CA (by K.K. Bradbury and J. Evans), and at the IODP Gulf Coast
Repository (GCR) in College Station, TX (by K.K. Bradbury and J. Evans). The descriptions (Appendix A2 Table A2) are expanded from those we prepared for the Core Photo Atlas (www.earthscope.org/safod) based on drill site descriptions. We used standard well-site and core-logging methods (Blackbourn, 1990), optical microscopy, X-ray diffraction, and X-ray fluorescence to characterize the lithology, meso- to micro-scale structure, mineral composition, and geochemistry in the near-fault environment. Detailed sample analyses were based on thirty samples taken at approximately 65 cm spacing over the entire depth range of Phase 3 spot core. Additional analyses of samples from Phase 3 core are reported in the Phase 3 Core Photo Atlas (www.earthscope.org/safod) and in several other publications [e.g., Bradbury and Evans, 2010; Chester et al., 2010; Hadizadeh et al., 2010; Holdsworth et al., 2011; Janssen et al., 2010, 2011; Lockner et al., 2011; Mittempergher, et al., 2011; Moore and Rymer, 2011; Morrow et al., 2010; Rybacki et al., 2010; Schleicher et al., 2010; van Diggelen et al., 2010; White and Kennedy, 2010]. Phase 3 core contain a compositionally heterogeneous mix of clastic sedimentary rocks fractured and sheared to different degrees (Appendix A1 Table A1; Figs. 3-2 – 3-4). We divide the core into several basic lithologic/structural units: arkosic sandstone (3141.4 - 3144.6 m MD and 3145.8 - 3152.6 m MD), black silty shale (3144.6 - 3145.8 m MD), black ultrafine-grained cataclasite (3193.9 – 3196.4 m MD), foliated phyllosilicate-rich fine-grained rock with heterogeneous clasts and/or interlayers that together display an overall block-in-matrix texture where blocks are composed of siltstone, sandstone, and shale (3186.7 - 3193.9 m MD, 3198.4 - 3199.5 m MD, 3294.9 – 3296.6, and 3299.1 - 3312.7 m MD), and pronounced zones of foliated fault gouge.
Figure 3-3. Schematic illustration of the complex internal structure of Phase 3 core and corresponding mineralogical or elemental trends. Also refer to Fig. 3-S5 for a summary of geochemical data. Line weight thicknesses reflect the relative quantity of each mineral constituent within a particular sample as examined through whole-rock geochemical methods (XRD and/or XRF). Greater line thickness corresponds to a greater relative abundance whereas thin lines represent present in moderate to small quantities within the sample analyzed, and dashed lines indicate a discontinuous or localized distribution. The most notable trends include: 1) the presence of large amounts of serpentinite (lizardite ± chrysotile) and saponite within the SDZ and CDZ; 2) quartz and feldspars decrease within the SDZ and CDZ; 3) magnetite and garnet phases along with pyrite mineralization border the SDZ and CDZ and increase locally within block-in-matrix materials; and 4) Nickel-oxides and chromium-oxides show elevated concentrations in the narrow zones of the SDZ and CDZ; 5) carbonates increase within the broader shear zone including the two narrow zones of the SDZ and CDZ; and 5) palygorskite is present locally throughout much of the core (likely associated with fracture fillings) but is not within the SDZ and only present in the very base of the CDZ.
associated with the SDZ and CDZ (3196.4 – 3198 m MD and 3296.6 - 3299.1, respectively). The majority of the core is intensely fractured and sheared. The matrix of the gouge in these zones exhibits a pervasive foliation wrapping around isolated cm-scale clasts that have a strong preferred orientation (Sills, 2010; Sills et al., 2009). The westernmost multilateral hole (Hole E) encountered a mixture of arkosic sandstones and fine-grained sedimentary rocks. Three distinct rock types exist (Appendix A1 Table A1; Fig. 3-2 – 3-3): 1) a greenish-gray to dark-greenish gray lithic arkose (Fig. 3-4A); 2) a dark grayish-black silty shale/mudstone with coarser interlayers (Fig. 3-4B); and 3) a brownish-red feldspathic arkosic sandstone (Fig. 3-S1A-D).

Thin white veins that are less than a mm in width and mm- to cm in length cut the green arkosic sandstone, and are oriented sub-parallel and oblique to the core axis. Several clasts within the arkosic sandstones are offset up to several millimeters by this fracture system (Fig. 3-4A). A second through-going fracture set, distinguished by dark reddish-brown staining, is oriented ~ 70°-130° relative to the axis of the core, and has an average spacing of ~ 30 cm (Fig. 3-S2A). Zircon fission-track dates of cuttings from approximately the same depth suggest an average age for these rocks of approximately 64 to 70 Ma ago (Springer et al., 2009). Samples contain abundant quartz and feldspar, and minor amounts of muscovite, biotite, magnetite, chlorite, serpentine, and pyroxene (Appendix A1 Table A1). Subrounded to angular grains are supported by a fine-grained mixture of illite-smectite clays and scattered zeolites (Appendix A2 Table A2; Figs. 3-5A and 3-S2A). XRF analyses indicate relatively high concentrations of Al₂O₃, likely
reflecting the abundance of clays within the fine-grained matrix (Appendix A3 Table A3). In thin-section, several grains show irregular boundaries, elongated geometries, and pressure solution seams (Fig. 3-5A-C).

Figure 3-S1. Additional images of representative lithologies and structural features present within Phase 3 Core: A) reddish-brown arkose shown in cross-sectional view in Fig. 3-4C at 3151 m; B) black staining and clay alteration on open fracture surface; C) black staining (carbon rich?) along contact between fracture surface and sheared shale surface shown in b); D) finely laminated and interbedded siltstone and shales. Note carbonate veins in siltstone layers/blocks do not extend into surrounding shaley layers while shale is smeared along small-scale slip surfaces; and e) matrix of shaley layers continues to be friable with a sheared and/or shiny luster on nearly every open fracture surface.
Figure 3-4. Images of representative lithologies and structural features present within Phase 3 Core:  A) green arkosic sequence at 3142 m with coarse feldspar fragments and volcanic lithic fragments showing small-scale offsets; B) sheared black silty shale/mudstone at 3144.6 m with exposed fracture surface exhibiting vitreous luster and a greenish hue; C) View of reddish-brown arkosic unit parallel to axis of core; D) penetrative anastomosing fabric and cataclasite within sheared black rock at 3193.7 m (Appendix A1 Table A1). Carbonate veins and cataclasite are interlayered with black staining parallel to the foliation direction; E) shiny surfaces are common along sheets separated from the core and parallel to the plane of foliation in the sheared black rock; F) pinch-and-swell shaped clasts entrained within matrix materials forming a heterogeneous block-in-matrix structure; G) fine-grained siltstone clast with a slightly folded shape yet significantly less deformed than surrounding friable matrix; and H) sheared shaley matrix and large siltstone clasts near ~ 3311 m MD that highlight the overall trend of larger clasts exhibiting less intense deformation with fewer intraclast veins near the base of Phase 3 core.
Figure 3-5. Deformation at the micro-sale in Hole E core material sampled (Fig. 3-S2) west of the main trace of the SAF plate boundary (Figs. 3-1 – 3-2): A) view under cross polarizer light of carbonate alteration and clay development within this matrix supported unit and also along adjacent intergranular microfractures (see white arrow) where it appears that progressive grain elongation occurs adjacent to outer margins of the slip zone; deformation lamellae are present in quartz grains in the upper left in and middle bottom photo; grain boundary migration (gbr) features in quartz grains suggest low temperature, fluid alteration and neocrystallization and/or high strain recrystallization; larger dark quartz grain shows evidence for pressure solution (ps) that extends into surrounding matrix; indentation, interpenetration, and truncation of grains are evidence for diffusive mass transfer processes (Blenkinsop, 2000; Rutter, 1983); B) myrmekite intergrowths and fractured feldspar in grains floating within the clayey matrix; pressure solution seams occur in several grains; C) thin-section photograph illustrates angular grains boundaries, distinct green grains with abundant magnetite, and the presence of pressure solution seams; D) At 3147.5 m MD as viewed under cross polarizer light, reactivated fractures and multi-layered cataclasite plus associated microscale fracturing are evidence for multiple episodes of slip. Note the bounding slip surface is coated with dark iron-oxides (magnetite?) and neocrystallized clay. Beyond the boundaries of the main slip surfaces, grains are intensely fractured and show additional evidence for various stages of cataclasis between fractured grains and the subsequent healing of fractures.
Figure 3-S2. Meso-scale deformation observed in Hole E core sampled west of the main trace of the SAF plate boundary (Figs. 3-1 – 3-2, 3-4): A) Evidence for low-temperature deformation and fluid-rock interactions are indicated by white arrows within the green-arkosic unit and include highly altered feldspars, reddish-brown staining parallel to fracture surfaces, and white hairline veins (Refer to Figure 3-4A-B); B) sheared and highly fractured black shale with distinct glassy fracture surfaces that separates the two arkosic units in Hole E (Refer to Figure 3-4C); C) cataclasite bands offset by younger phase of slip and cataclasite generation (Refer to Figure 3-4D); D) slickenlined fracture surfaces are common throughout this unit (Refer to Figure 3-4D).

At 3144.6 m MD, a ~ 0.5 m thick interval composed of dark grayish-black silty shale/mudstone (Appendix A1 Table A1; Fig. 3-2) is juxtaposed with the green lithic arkose along a sharp boundary. The most notable features in the shale/mudstone interval are polished and slickenlined fracture surfaces that have a distinct vitreous luster or
mineralization (Figs. 3-4B and 3-S2B). The larger, elongate, sub-angular to angular quartz and feldspar grains surrounded by fine matrix within the fractures display a weak preferred orientation, consistent with deformation and/or low-temperature neocrystallization/alteration processes (Figs. 3-5A-C; Appendix A1 Table A1; Ree et al., 2005; Yan et al., 1997). A distinct altered green mineral (serpentine, chlorite, and/or palygorskite?) and associated magnetite are present in the coarser layers. Abundant opaque oxide/hydroxide grains are scattered throughout the finer-grained matrix, and are concentrated within microstylolites and irregularly shaped regions. At 3144.6 m MD, the main mineral constituents identified by XRD are quartz and plagioclase, with minor amounts of magnetite, palygorskite(?), illite, and lizardite (Appendix A2 Table A2).

Lithologically, this unit is similar to rocks of the 3067 m MD fault, cored during Phase 1 (Springer et al., 2009; http://www.icdp-online.org/). Major element analyses, however, indicate that the shale/mudstone unit sampled during Phase 3 has relatively higher concentrations of Al$_2$O$_3$ and TiO$_2$, with a corresponding decrease in silica (Appendix A3 Table A3). Near the base or eastern boundary of this unit (~3145.8 m MD), a thin discontinuous lens of light olive-gray siltstone forms the contact with arkosic sandstone (Appendix A1 Table A1; Fig. 3-2). This contact is oriented at a moderate- to high-angle to the core axis. Pressure solution seams and small-scale offsets are also present near this contact (Fig. 3-5C).

Lower in Hole E, a reddish-brown arkosic sandstone is encountered (Figs. 3-2 – 3-3 and 2-4C). This unit is similar to the Paleocene- to Eocene arkosic sequence sampled during Phase 2 drilling and described in detail by Springer et al. (2009). Potential source
rocks for the unit includes the Salinian granitic terrain and associated volcanic arc rocks (Springer et al., 2009). Dark-reddish brown lamina and coarse layers (~ 0°- 20° relative to the core axis) are offset by several through-going conjugate slip surfaces oriented at 55°-120° to the core axis with a minimum ≤ 10 cm spacing. Many of these surfaces bound mm-cm thick zones of cataclasite (Fig. 3-S2C). Another predominate set of slip surfaces, having apparent offsets of less than 3 cm, intersect the core and are characterized by a straight fracture surface morphology. This latter set is commonly coated with a thin film of red to white clay or displays polished slickenlines that are parallel to the apparent dip (relative to the core axis) of the fracture (Fig. 3-S2D; 30°-60° to the core axis). The primary minerals in the sandstone include quartz, feldspar, and mica (Appendix A2 Table A2). XRD analyses of the fracture coatings reveal smectite (nontronite?) clay, calcite, ± laumontite, and ± palygorskite (Appendix A2 Table A2). Pressure solution seams are comprised of fine-grained clays and/or opaque oxides/hydroxides. These features are roughly oriented sub-parallel and oblique to the dominant through-going fracture set. Microscale analyses show multiple episodes of cataclasite generation in zones < 1mm to 5 mm thick (Fig. 3-5D). Deformation extends beyond the discrete slip surfaces for several mm where quartz and feldspar grains greater than 0.5 mm are intensely fractured, altered, and locally show evidence for pressure solution (Fig. 3-5D). Development of irregular quartz grain morphologies surrounded by an interlocking network of fine-grained clay, quartz, and feldspar (Fig. 3-5D) suggest dissolution and neocrystallization associated with low-temperature alteration and/or fluid-rock interactions (Ree et al., 2005; Yan et al., 1997). Whole-rock geochemistry (XRF) of
the arkosic sandstones west of the SDZ show elevated concentrations of SiO$_2$, Al$_2$O$_3$, CaO, K$_2$O, and Na$_2$O and decreased concentrations of FeO, MgO, relative to rocks sampled east of the SDZ and/or deeper in the borehole. The fracture surfaces that are coated with clays and oxides/hydroxides are one exception to the above (Appendix A3 Table A3).

Core was not collected between 3152.6 – 3186.7 m MD (Fig. 3-2). Over this interval, the wireline logs recorded abrupt reductions in $V_p$ and $V_s$ in the vicinity of 3155 m MD (Zoback et al., 2010; Fig. 3-1D). These velocity reductions are interpreted to represent the change in composition from arkosic sandstone to rocks rich in phyllosilicates (Jeppson et al., 2010; Zoback et al., 2010). A noticeable increase in cataclasite was found in the cuttings within this interval (Bradbury et al., 2007) suggesting that this sharp boundary represents a fault.

Core collected in Hole G, from 3186.7 to 3199.5 m MD, captured a foliated cataclasite, locally displaying block-in-matrix structures, that contains clasts and blocks of siltstones and very-fine grained sandstones, and a ~3 meter interval of very fine-grained, cohesive, massive black rock (~3193.9 to 3196.4) that is interpreted to be an ultracataclasite (e.g., Janssen et al., 2010). The fine-grained matrix of the foliated cataclasite is cut by a few narrow shear zones and displays a penetrative scaly fabric that is similar to an argille scaglioise fabric (Bianconi, 1840; Camerlenghi and Pini, 2009; Cowan, 1985; Pini, 1999; Vannucchi et al., 2003). The cataclasite matrix surrounds elongate, irregular-shapes lenses, clasts, and larger blocks of the sedimentary host rocks. Several clasts exhibit pinch-and-swell structures and are laced with thin, short calcite
veins that do not extend into the surrounding matrix. These veins often are oriented at high angles to the matrix foliation. Black, irregular, injection-like features occur near fracture surfaces at ~3186.8, 3192.5, 3193.7, and 3989.7 m MD (Figs. 3-2, 3-4, 3-S1, and 3-S3; Appendix A1 Table A1).

The foliated gouge of the SDZ (Zoback et al., 2010) was intersected between 3196.4 and 3198 m MD. The boundary of the gouge with the foliated cataclasite to the west is sharp, compositionally distinct, and oriented at a high angle to the core axis (Figs. 3-2, 3-3, and 3-7). The matrix of the gouge is an incohesive, dark grayish-black to greenish-black phyllosilicate-rich, ultra fine-grained zone that displays a scaly fabric with pronounced anastomosing polished slip surfaces. Clasts of the surrounding host rocks, including serpentine, are dispersed throughout the gouge and account for up to 10% of the total gouge volume (Sills, 2010) (Appendix A1 Table A1; Fig. 3-S3D). In contrast to the pinch-and-swell textures and fractured clasts of the foliated cataclasites to the east, the clasts within the foliated gouge are elongate, have smooth boundaries (Sills, 2010), and exhibit a greater degree of alteration (Fig. 3-7). Lens-shaped fragments or phacoids of the gouge matrix (Figs. 3-S3D and 3-7), split apart easily and reveal polished and sometimes striated surfaces. A ~ 30 cm thick block of massive, serpentine occurs within the foliated gouge interval. The boundaries of this block also are sharp and oriented at a high angle to the core axis. The block is cut by numerous white (calcite and chrysotile) veins that are up to several mm-thick and are oriented sub-parallel to the core axis (Fig. 3-7). The eastern boundary of the serpentine block is defined by a 4-cm-thick zone of altered and sheared blue-green serpentine that displays an earthy luster and contains
fragmented veins oriented roughly perpendicular to the core axis. (Appendix A1 Table A1; Fig. 3-7A). Clasts of serpentine within the core catcher are sheared and appear altered, and generally are elongated parallel to the foliation (Figs. 3-S3D and 3-7).

Figure 3-S3. Deformation and alteration adjacent to the SDZ of Zoback et al. (2010) at the meso-scale: A) Between 3186.7 to 3193.3 m MD, the rocks within the foliated cataclasite unit exhibit an alignment of phyllosilicates and oxides within the finer matrix materials from the meso- to micro-scale (See also Fig. 3-6) and cataclasite features surrounding clasts of various lithologies and/or compacted cataclasite support fluid-like injection and brecciation processes (Fig. 3-6B); B) black staining associated with fracture system near 3192.5 m MD; C) Sheared interval of black fault-related rock/cataclasite along the western boundary of the SDZ (See also Fig. 3-6E-F); and d) scaly clay fabric from the core catcher at 3197.8 m MD (Refer also to Fig. 3-6G-H) correlates to the rocks associated with active casing deformation near ~ 3192 m MD in the borehole.
The small section of core captured to the east of the SDZ in Hole G displays considerably less deformed sedimentary rock. Within the blocks or interlayers, bedding is intact and defines alternating layers of finely laminated, light gray to gray-green, fine-grained silty sandstone and silty shale/mudstone (Fig. 3-S1D). Calcite veins dissect the silty sandstone but terminate abruptly against the shaley layers (Fig.3-S1D). Contacts between laminae in some cases appear to be dark seams with stylolitic geometries and may suggest solution processes. Clay smears are developed along the mesoscopic slip surfaces that are oriented at high-angles to the core axis. Quartz and plagioclase (albite) are the predominate minerals comprising the siltstone layers. Veins of calcite and chlorite ± smectite ± illite phases are noted in the sheared shaley layers (Appendix A2 Table A2ab). Serpentine (lizardite and chrysotile) was also noted in some analyses of the clasts within the foliated gouge materials at 3197.9 m MD (Appendix A2 Table A2). No core was collected between 3199.5 m MD and 3294.9 m MD. Hole G (Runs 4, 5, and 6) captures rock from 3294.9 - 3312.7 m MD. Over this interval the lithology and deformation vary significantly. Core Run 4 intersected a distinctive, interlayered Mg-rich siltstone and sandstone unit that is cut by numerous mesoscale faults and finer, more distributed shear surfaces (Appendix A1 Table A1-A2).

The foliated gouge layer of the CDZ was intersected between 3296.6 and 3299.1 m MD, correlating to the region of active casing deformation at 3302 m MD in the main borehole (Appendix A1 Table A1; Figs. 3-1 – 3-3, 3-8, 3-S4; Zoback et al., 2010). The matrix of the CDZ is remarkably similar to that of the SDZ, consisting of phyllosilicate-rich gouge with a penetrative foliation that is oriented approximately perpendicular to the
core axis (Fig. 3-S4). Like the SDZ, the gouge contains matrix-supported, elongate clasts that parallel the foliation (Figs. 3-S5 and 3-8A-B; Sills et al., 2009). The boundaries of several clasts are sheared, and many display numerous calcite veins, some up to 1 to 2 mm wide (Fig. 3-8B). Whole-rock XRD powder samples near ~ 3297 m MD indicate the presence of saponite, serpentine (lizardite ± chrysotile), quartz, and feldspar (Appendix A2 Table A2). Geochemical data from this interval show significantly elevated concentrations of MgO and Ni-oxides, suggesting potential fluid-assisted alteration of serpentinite (Appendix A3 Table A3; Fig. 3-S5; O’ Hanley, 1996). These data are consistent with those reported by others (e.g., Holdsworth et al., 2010; Moore and Rymer, 2009, 2010; Schleichler et al., 2010).

East of the CDZ, there is a mixture of alternating fine-grained sandstone, siltstone, and shale that is fractured and sheared to varying degrees. The dimensions of deformed blocks range up to 190 mm (Figs. 3-4 and 3-S1). The long axes of the blocks exhibit a preferred orientation that is inclined ~ 40° to 90° to the core axis. In general, the block size increases towards the base of Hole G with a corresponding decrease in block asymmetry. Exceptions to the overall trend occur within the comminuted, fine-grained shear zones. Slip surfaces bounding the blocks, and layers of cataclasite, breccia, and noncohesive rubble are inclined ~ 40 to 50° to the core axis. Polished, striated surfaces on disaggregated fragments are nearly ubiquitous throughout Hole G. Meso-scale sulfide lenses, concretions, and nodules are present throughout the core and increase in occurrence towards the base of Hole G. Gouge and other highly sheared fault-related rocks within Hole G (Black fault-related rock, SDZ, and CDZ in Appendix A1 Table A1)
account for over 13 % by volume of the total core sampled. Cuttings below ~3313 m MD contain a greater number of cataclasite fragments and show a greater degree of alteration (Bradbury et al., 2007), supporting the suggestion that fault-related damage extends further east and to deeper depths (Zoback et al., 2010).

Numerous veins, approximately 1-mm-thick, cut the Phase 3 core. These primarily are concentrated within the sandstones, but also lace the serpentinite blocks and the black ultra-fine grained rocks surrounding the SDZ and CDZ (Figs. 3-6 and 3-7). Cross-cutting relationships suggest that there were at least two episodes of vein formation (Figs. 3-6 – 3-8).
Figure 3-6. Deformation and alteration adjacent to the SDZ of Zoback et al. (2010): A) Between 3186.7 to 3193.3 m MD, the rocks within the foliated cataclasite unit exhibit an alignment of phyllosilicates and oxides (denoted by white arrow) within the finer matrix materials from the meso- to micro-scale; B) cataclasite in fractures surrounds or dissects clasts of various lithologies, supporting fluid-like injection and brecciation processes; C) well-developed foliation within phyllosilicate-rich gouge and rough alignment of quartz and various altered grains; note high-angle open hairline fracture system (marked by white lines) dissects foliation direction (white arrows); d) at 3192.8 m MD a silty-shale clast (white dashed-lines) is mantled with clay and attached to adjacent fragment of compacted gouge (?), forming flow patterns within the matrix; note high angle fractures (solid white lines) are coated with iron-oxides (magnetite) and dissect the foliated matrix; E) the black fault-related rock exhibits multiple episodes of fault slip offsetting ultracataclasite layers with several phases of mineralization related to fluid-rock interactions as evident by vein geometries and compositions (Appendix A2 Table A2) and the concentration of opaque minerals (magnetite) parallel to the foliation direction; F) slip localization (white arrow) within clay and serpentine-rich (lizardite ± chrysotile) gouge; a crosscutting network of veins and open fractures is also observed; g) Cr-spinel (shown by white arrow) and andradite garnet (see Appendix A2 Table A2) are identified as porphyroclasts in the fault gouge of the SDZ; h) altered lithics and calcite are embedded within sheared phyllosilicate-rich matrix that characterizes the texture of the SDZ fault gouge.
Figure 3-7. Rocks associated with the SDZ zone of casing deformation as measured in the geophysical logs near ~ 3192 m MD (Zoback et al., 2010) otherwise identified as Hole G Run 2 Section 7 Phase 3 SAFOD core. Due to the geological significance of this core, no samples have been taken to date: A) sketch of the internal structure highlighting cm-scale zones of finite width with varying composition and textures; B) and C) thin-section grain mounts at 3197.0 m MD are comprised of lizardite and chrysotile (foliated clast) based on XRD analyses; calcite, quartz, and ordered interlayered chlorite-smectite clays were also identified (Appendix A2 Table A2b); D) foliated phyllosilicate-rich fault gouge at 3197.1 m MD is comprised of quartz, plagioclase, illite, and caclite with interlayered chlorite-smectite ± chlorite ± smectite ± serpentine (Appendix A2 Table A2b); E) view of clay mantled clast in plane polarized light, note concentration of magnetite grains surrounding clast that are likely associated with serpentine minerals; and F) view in polarized light with gypsum plate inserted highlights intraclast deformation with domaval fabrics due to recrystallization processes.
Figure 3-8. Deformation and alteration adjacent to and within casing deformation near 3302 m MD or the CDZ of Zoback et al. (2010): A) scaly clay fabric in the fault gouge illustrating both distributed deformation and slip localization within the discrete fracture zones near the right edge of the photo; B) development of S-C fabric in serpentinite-bearing clay gouge is highlighted; opaque stringers or grains are comprised of magnetite and appear concentrated within regions associated with altered clasts; clasts (cl) and altered clasts (acl) show development of preferred orientation through rotation in the fine matrix. View is under cross-polarizer light with gypsum plate inserted; C) altered and reworked cataclasite grain embedded within the fine foliated phyllosilicate-rich matrix support repeated episodes of brittle deformation; abundant calcite veins dissect the cataclasite; view is under cross polarizer light; D) highly rounded, clay mantled, and altered serpentinite (lizardite ± chrysotile) clast within the fault gouge; E) volcanic lithic clast (basic or basalt composition) documents variability within clast compositions and the great degree of mixing within the fault gouge; and F) photomicrograph of scaly clay fabric dissected by numerous carbonate veins.
Figure 3-S4. Deformation and alteration adjacent to and within casing deformation near 3302 m MD or the CDZ of Zoback et al. (2010): A) close-up image of foliated fault core gouge with large clay mantled and partially altered clast of serpentinite (lizardite); B) close up image of the core at 3297.8 m MD showing the orientation of the fabric is generally perpendicular to the core axis (redline); note green, rounded or eye shaped clasts embedded in the finer matrix. Refer to Fig. 3-8 for micro-scale observations near this depth.
Discussion

We characterize the SAFOD Phase 3 core samples from the San Andreas Fault zone at approximately ~ 3 km depth as compositionally heterogeneous and structurally complex at the meter scale, i.e., at a scale that is important to earthquake rupture nucleation and propagation (Sibson, 2003). The ~ 41 m of core is comprised of a mixture of fractured arkosic sandstones, penetratively sheared siltstones and shales, cataclasite to ultracataclasite, and foliated serpentinite-bearing clay fault gouge, alternating with blocks of less-deformed fine-grained sandstone and siltstone. Over 60% by volume of the core is comprised of sheared phyllosilicate-rich layers, gouge and ultracataclasite, and lenses of other fault-related rocks (Fig. 3-2).

West of the SDZ, at a MD of approximately 3150 m (Zoback et al., 2010), the arkosic rocks exhibit localized brittle structures documenting evidence for repeated episodes of deformation. These structures display variations in the composition and texture of fracture-fill, differences in shear fracture morphology, and distinct cross-cutting relationships (Tables A1-A3). The structural relations are consistent with episodic fluid-rock interactions and brittle fault-related damage generation associated with slip on the San Andreas Fault. Generation of fault-related damage farther west of 3150 m MD also is indicated by structures observed in image logs, features of cuttings, and core-samples collected during Phases 1 and 2 (Bradbury et al., 2007; Springer et al., 2009). The approximately 200 m-thick damage zone identified between 3192 and 3413 m MD on the basis of seismic velocity, resistivity and other log data (Zoback et al., 2010) is likely a minimum estimate of the total extent of fault-related damage. On the basis of
core studies, a better estimate would be at least 350 m, starting at 3050 m MD (Chester et al., 2007, 2010; Heron et al., 2011; Jeppson et al., 2010). The intensity of damage does not appear uniform within this interval, and likely reflects the presence of multiple principal slip surfaces and fault-related rock lenses with overlapping damage zones. In addition, it is unlikely that all surfaces and damage zones are active at any one time (Chester et al., 2010; Malin et al., 2006).

Along the western boundary of the SDZ, the sheared black and black-stained rocks (Figs. 2-4 and 2-S1) that contain injection structures (Figs. 3-6E-F and 3-S3B-C) and foliated cataclasite (Fig. 2-6E-F) are unique. Geochemical analyses indicate that these rocks are rich in carbonaceous material (Fig. 2-3). The localized black staining may indicate hydrocarbons are migrating or have recently migrated along fractures in the SDZ. Two distinct mud gas-rich zones were identified in the SAFOD borehole at 2700 - 2900 m MD and at depths greater than 3550 m MD. Smaller interstratified lenses rich in CO₂ and hydrocarbons were found between 3150-3200 m MD, and nearly pure hydrocarbons exist between 3310-3340 m MD (Fig. 3-2; Wiersberg and Erzinger; 2008). Additionally, small tar seeps are present along the surface trace of the SAF up-dip of the SAFOD borehole. Oxygen and carbon isotopes within carbonate veins located throughout the Phase 3 core, including the SDZ and CDZ, also are consistent with carbonates having precipitated from a fluid charged with hydrocarbons (Kirschner et al., 2008). Given the regional geology, the source of hydrocarbons likely is the Great Valley Formation (Ingersoll et al., 1977).
Janssen et al. (2010) cited evidence for comminuted materials similar to crush-origin pseudotachylytes within the black rocks at ~3194 m MD, based on SEM and TEM observations, and Holdsworth et al. (2011) suggests these textures are related to local fluidization or injection during transient overpressure of pore fluids during slip events. Similar features are found in active and ancient fault zones elsewhere and have been attributed to a mixture of comminution, fluidization, and thermal pressurization processes (Brodsky et al., 2009; Meneghini et al., 2010; Rowe et al., 2005; Ujiie et al., 2007; Wibberley and Shimamoto, 2005). While we observe injection- and fluidization-type features at the microscale (Fig. 3-6B), diagnostic evidence for pseudotachylyte in our samples is absent at the optical scale. Accordingly, the black rocks (Figs. 3-6 and 3-S3) may reflect: 1) ancient ultracataclasite, and thus, as suggested by Holdsworth et al. (2011) could be regions that slipped seismically in the past; 2) a concentration of damage associated with repeated microearthquakes; and 3) hydrocarbon migration and gas-charged fluids entering fractures during deformation, associated with transient fluid pressure changes (Mittempergher et al., 2011).

The block-in-matrix structures and scaly clay fabrics that characterize the regions surrounding the SDZ and CDZ (Figs. 3-3 – 3-4) are similar to block-in-matrix structures of sedimentary rock in tectonic mélange (Festa et al., 2010; Hsü, 1968; Medley and Goodman, 1994; Raymond, 1984). Although similar scaly clay fabrics are observed in numerous exhumed exposures of Franciscan mélange and in sheared serpentinite outcrops within the San Andreas Fault system (Bradbury and Evans, 2009; Moore and Rymer, 2009, 2010), these rocks do not display diagnostic mineralogical assemblages or
conclusive evidence of originating from the Franciscan tectonic mélange. The rocks may result from 1) repeated episodes of deformation, fragmentation, and mixing related to strike-slip faulting (Fagereng and Sibson, 2010; Festa et al., 2010) producing foliated cataclasite; 2) pre-SAF deformation of the protolith, e.g. slivers of altered Franciscan mélange entrained within the fault zone; or 3) a combination of SAF-related shearing superposed on the initial block-and-matrix mélange fabric. Given the penetrative nature of the thin, anastomosing surfaces within the matrix encompassing the blocks, the block-in-matrix structure may reflect continuous deformation processes related to aseismic creep and stable frictional sliding (Colletini et al., 2009; Faulkner et al., 2003).

The penetrative and highly sheared scaly fabric of the serpentinite-bearing, clay-rich fault gouge that correlates with the actively creeping SDZ and CDZ, reflects the presence of meso- to micro-scale anastomosing slip surfaces that are coated with clays and opaque oxide-hydroxides. These surfaces locally weave around lens-shaped porphyroclasts of compacted matrix material (Sills, 2010), reworked cataclasite, and other lithologies, and display striated and polished slip surfaces (Figs. 3–6 – 3-8). Schleicher et al. (2010) identify illite-smectite and chlorite-smectite as the main phases comprising the clay coatings along such surfaces within the matrix materials near ~3066 m and ~3300 m MD, and suggest these coatings may influence slip and aseismic creep through dissolution-precipitation processes. Experimental work on clay-rich samples from SAFOD and other exhumed fault-related rocks also demonstrates the potential for clay to influence the frictional properties of clay-lined fractures (e.g., Morrow et al., 2007; Solum and van der Pluijim, 2009; Tembe et al., 2006).
The composition and distribution of serpentinite and related alteration products may play a key role in the evolving mechanical behavior of the SAF system in the region (Moore and Rymer, 2007, 2009, 2010; Moore et al., 1996, 1997; Reinen et al., 1991). Saponite, the Mg-rich smectite phase that is an alteration product of serpentinite in the presence of fluids (e.g., Moore and Rymer, 2010), is very abundant within the SDZ and CDZ gouge (Appendix A2 Table A2) and frequently comprises alteration rims on serpentinite clasts. Saponite is very weak in shear and displays a coefficient of sliding friction that approaches \( \mu = 0.05 \) (Lockner et al., 2011; Morrow et al., 2010). The XRD analyses of samples indicate the foliated gouge contains significant quantities of lizardite and chrysotile. Experimental work has demonstrated that small amounts (<15% bulk wt. %) of serpentine may significantly reduce the overall frictional strength of fine-grained materials (Escartin et al., 2001), though even high concentrations of serpentine do not lead to friction coefficients as low as seen in smectites (e.g., Andreani et al., 2005; Evans, 2004; Moore et al., 1996, 1997; Morrow et al., 1984, 2000; Reinen, 2000). Many previous field studies have noted the presence of serpentinite and weak clays along the central segment of the SAF, and numerous laboratory experiments have explored the mechanical role of these phases in promoting fault creep (e.g., Allen, 1968; Ikari et al., 2009; Irwin and Barnes, 1975; Reinen et al., 1991). Data from these studies suggest that these phases can explain fault zone weakening, nondilatant brittle deformation, and the aseismic creep, and they may influence the fluid-flow properties of the fault zone locally (e.g., Carpenter et al., 2009, 2011; Escartin, et al., 1997; Lockner et al., 2011; Morrow et al., 2000, 2007; Schleicher et al., 2009; Solum and van der Pluijm, 2009). These
suggestions are supported by the correlation of active creep in the chemically and mineralogically distinct foliated gouge layers rich in serpentine and saponite (e.g., Moore and Rymer, 2010).

Geochemical data from the core shows that the major element composition of the SDZ and CDZ is dramatically different than the surrounding rocks (Bradbury and Evans, 2010). This is consistent with data presented by Holdsworth et al. (2011) on several other samples. Core samples from rock in Hole E, and farther west, have higher levels of Al$_2$O$_3$ with moderate to higher levels of SiO$_2$ as compared to core samples taken to the east (Fig. 3-S5A). In the SDZ, MgO concentrations are elevated significantly compared to surrounding host rocks and show a corresponding decrease in SiO$_2$ (Fig. 3-S5C). SiO$_2$ concentrations are variable in sampled rocks between the SDZ and CDZ and are associated with relative increases in Al$_2$O$_3$ or CaO (Fig. 3-S5D). Within the CDZ, MgO concentrations are once again elevated with SiO$_2$ decreasing (Fig. 2-S5E). In both the SDZ and CDZ, elemental Ni and Cr concentrations are elevated (Appendix A3 Table A3), approaching ore-grade values (Candela and Piccoli, 2005), and may suggest either significant fluid-assisted alteration of serpentine to clay (O’Hanley, 1996) or represent mineralogical signatures potentially inherited from the protolith material. East of the CDZ to ~ 3313 m MD, SiO$_2$ levels are again highly variable with associated increases in Al$_2$O$_3$ levels (Fig. 3-S5F).

Isotopic data identifies at least two populations of carbonate veins showing variable composition in the host rocks, whereas elements such as strontium and calcium are more uniformly distributed inside the foliated gouge of the SDZ and CDZ (Kirschner
et al., 2008). Thus, it appears the incorporation of serpentinite into the two layers of foliated gouge, mechanical mixing and grain size reduction, and the alteration to clay, combine to produce profoundly weak layers of gouge and promote long-lived concentrated shear and aseismic creep along the SDZ and CDZ intersected by the borehole at SAFOD.

Conclusions

*In situ* sampling and laboratory analysis of SAFOD Phase 3 core samples provides an opportunity to characterize the composition, internal structure, and weakening processes of an active fault zone undergoing shear and fluid-rock reactions at approximately 3 km depth. Combining core-scale descriptions and analysis of 30 samples collected across the SAF zone, we find the fault zone consists of broad zone of variable damage (> 300 m wide) that surrounds multiple narrower zones of highly sheared and altered rock containing complex internal structures. West of the SDZ, arkosic sequences and shales exhibit brittle deformation features and evidence of cementation. Adjacent to the southwest boundary of the SDZ, black fault-related rocks contain evidence of multiple episodes of slip and cataclasite and ultracataclasite generation with increases in magnetite, iron-sulfides, and organic carbon. Serpentinite- and smectite-bearing foliated gouge layers correlating with the SDZ and CDZ display highly sheared, scaly fabrics with a significant enrichment in Mg-rich clays, and Ni- and Cr-oxides relative to the surrounding rocks. The northeastern boundary of the CDZ is characterized by increases in magnetite and iron-sulfide. These data point to the influence of both mechanical and
chemical processes of weakening and localization of shear to at least two discrete and active zones of creep in the SAFOD borehole.

Figure 3-S5. XRF whole-rock powder geochemistry of Phase 3 core samples. Major element variations for selected oxides relative to silica and illustrated as a function of structural position across the SAFOD borehole and SAF: A) On the Pacific plate between 3100-3150 m MD, higher concentrations of Al₂O₃ and SiO₂ are associated with Salinian granitoid and arkosic sedimentary rocks; B) On the North American Plate, between 3185 - 3195 m MD, the rocks have moderate Al₂O₃ and high SiO₂ concentrations associated with sheared fine-grained sandstones, siltstones and shales associated with the Franciscan and Great Valley protolith; C) In the SDZ, MgO concentrations are high whereas SiO₂ are very low due to the presence of serpentinite and smectitic clays; D) Between the SDZ and CDZ, Al₂O₃ and CaO concentrations are generally increasing with variable amounts of SiO₂ due to the presence clay alteration and localized carbonate veins; E) In the CDZ, MgO concentrations increase again with low SiO₂ as serpentinite and other phyllosilicates increase; and F) East of the CDZ, Al₂O₃ concentrations generally increase and SiO₂ concentrations show greater variability. XRF sample processing was completed by staff at Washington State University in the GeoAnalytical Laboratory, Pullman, Washington.


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CHAPTER 4

MICRO-SCALE COMPOSITION AND TEXTURE OF FAULT-RELATED ROCKS FROM SAFOD CORE: PHYSIO-CHEMICAL EVIDENCE FOR DEFORMATION PROCESSES AND FLUID-ROCK INTERACTIONS

Abstract

We examine the composition, alteration, and texture of fault-related rocks identified in San Andreas Fault Observatory at Depth (SAFOD) Phase 3 drilling core samples to provide insight into deformation and physio-chemical processes occurring within an actively creeping segment of the San Andreas Fault at ~ 3 km depth in the San Andreas Fault Observatory at Depth (SAFOD) borehole. Petrography and microstructure, electron microbeam and whole-rock geochemistry are used to characterize samples from core sampled between 3187.4 to 3301.4 m measured depths in the SAFOD borehole. The fault-related rocks consist of juxtaposed lenses of foliated siltstone and shale with block-in-matrix fabric, black cataclasite to ultracataclasite fault-related rock, and serpentinite-bearing, foliated fault gouge.

Zones of meters-thick fault gouge correlate to the regions of active casing deformation in the SAFOD borehole and are characterized by numerous anastomosing slip surfaces that surround conglobulated- to lens-shaped compacted clay and serpentinite clasts. The gouge matrix is composed of Mg-rich clays (saponite ± palygorskite), and serpentinite minerals (lizardite ± chrysotile). Whole-rock chemistry data show notable

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increases in Fe-, Mg-, Ni-, and Cr-oxides and hydroxides, Fe-sulfides, and carbonaceous material. Micro- to meso-scale fabrics create a distinct structural texture that is consistent with deformation processes related to aseismic deformation with periodic seismic slip. The composition and structure of the fault zone reflect a complex history of deformation and multiple fluid-rock interactions, that may contribute to the low-strength and deformation in the active SAF at shallow crustal levels in the vicinity of SAFOD.

Introduction

The development of well-constrained geological and geophysical models of active fault zones is a critical component to understanding earthquake behavior and may be used to develop more accurate constraints on the potential probability and distribution of earthquakes in the shallow crust (http://earthquake.usgs.gov). Earthquakes occur in rocks at depth (Fagereng and Toy, 2012; Sibson, 1975; 2003) yet until relatively recently (Boullier, et al., 2009; Cornet et al., 2004; Heermance et al., 2003; Hickman et al., 2004; 2007; Hirono et al., 2007; Ohtani et al., 2000; Tanaka et al., 2002; Tobin and Kinoshita, 2006; Townend et al., 2009; Zoback et al., 2007; 2010) sampling of rocks from within active plate-boundary fault zones has been limited. Direct knowledge of rock properties from active fault zones through the integration of drilling, field, and laboratory studies is necessary to identify the chemical and physical processes involved in fault zone deformation, to delineate the structural architecture of the near-fault environment, and to examine the potential role of fluids throughout the seismic cycle (Brodsky et al., 2010; Caine et al., 1996, 2010; Chester and Logan, 1986; Cowan, 1999; Evans and Chester,
Drilling of the San Andreas Fault Observatory at Depth (SAFOD; Figure 4-1) borehole near Parkfield, CA (Hickman et al., 2004, 2007; Zoback et al., 2010; www.earthscope.org/observatories/safod) enables us to examine in situ fault-related rock properties of the central creeping segment of the San Andreas Fault (SAF) from 0-4 km depth. The SAF near SAFOD creeps at the surface at a rate of 20 mm/yr (Titus et al., 2006) and coincides with a series of repeating microearthquakes occurring near 2500-2800 m vertical depth, about ~ 50 – 300 m from the fault zone as intersected by the borehole at SAFOD (Nadeau et al., 2004; Thurber et al., 2004; Zoback et al., 2010).

Serpentinite is commonly found in shear zone outcrops within the central SAF system (Allen, 1968; Irwin and Barnes, 1975; Moore and Rymer, 2012) and may be associated with regions of fault creep and deformation due their low range of frictional strength and mechanical behavior (Reinen, 2000; Reinen et al., 1991). Serpentinite-bearing fault gouge was identified in SAFOD samples (Bradbury et al., 2011; Moore and Rymer, 2007; Solum et al., 2006; Phase 3 Core Photo Atlas, www.earthscope.org/observatories/safod) in two ~ 1-2 m thick gouge zones associated with active creep and borehole casing deformation (Zoback et al., 2010). The two zones, referred to as the Southwest Deforming Zone (SDZ) at 3192 m MD and the Central Deforming Zone (CDZ) at 3302 m MD (after Zoback et al., 2010) are bounded by cohesive black fault-related rock composed of cataclasite, ultracataclasite, and sheared
siltstone and/or mudstone with block-in-matrix fabrics (Bradbury et al., 2011).

Recent analyses of whole-rock core suggests deformation and fault zone weakening in the SDZ and CDZ is likely influenced by: 1) the presence of neo-mineralized clay coatings on interconnected fracture surfaces (Holdsworth et al., 2011; Schleicher et al., 2010); 2) formation of amorphous materials related to syn-deformational fault lubrication (Janssen et al., 2010); 3) cataclasis, intense shearing and multi-phased veins related to episodic deformation and fluid-rock interactions (Bradbury et al., 2011; Rybacki et al., 2010; Schleichler et al., 2010); 4) dissolution-precipitation creep mechanisms (Gratier et al., 2011; Holdsworth et al., 2011; Mittempherger et al., 2011); and 5) presence and/or transformation of frictionally weak minerals such as clay, talc, and/or serpentine (Carpenter et al., 2011; Lockner et al., 2011; Moore and Rymer, 2007; 2012).

We examine the geologic and geochemical rock properties of fault-related rocks in the SAF at ~ 3 km depth in the SAFOD borehole. In this paper, we focus on the characterization of micro-scale compositional variations and microscopic damage textures of 3 fault-related rock units observed in SAFOD Phase 3 core (Bradbury et al., 2011), adjacent to and within actively deforming regions in the borehole. Detailed investigation of the SDZ and CDZ gouge reveals distinct compositional and structural features which bear a striking resemblance to rock samples collected from exhumed shear zones comprised of tectonic mélange and/or serpentine from central to northern California (Coleman, 1996; Dibblee, 1971; Dickinson, 1966; 1973; Moore and Rymer, 2012; Page et al., 1999; Rymer et al., 2004; Shervais et al., 2004; 2011; Sims, 1988; 1990). The structural features observed in exhumed analog outcrops may relate to active
deformation within shallow crustal levels of the SAF at SAFOD and may reflect both seismic and aseismic deformation processes coupled with episodic fluid-rock interactions.

Figure 4-1. Location and simplified vertical profile of the SAFOD borehole location with schematic of lithologic and structural units sampled. Refer to Bradbury et al. (2011) for a more complete review of the composition and structure of Phase 3 core. Core depths reported here are in meters measured depth along the main SAFOD borehole. For comparison to geophysical logs refer to Zoback et al. (2010) for depth correction methods. Inset map shows the location of the San Andreas Fault, SAFOD, and exhumed analog outcrops.

Micro-scale Composition and Texture of SAFOD Fault-related rocks

We examine variations of composition, structure, and alteration of Phase 3 whole-rock core samples using petrographic thin-section studies, X-ray diffraction (XRD), X-ray fluorescence (XRF) analyses, Scanning Electron Microscope (SEM) backscatter imaging, Total Organic Carbon (TOC) measurements, Loss on Ignition (LOI) values, and
the Chemical Index of Alteration (Nesbitt and Young, 1982) analyses (Table B1; Figures 4-6; 4-S1; 4-S2). Loose chips or slices of core ~ 1/8 - 1/3 of the core-diameter (d=10 cm) or as loose chips between 3185 m MD to 3315 m MD were collected. Detailed lithologic and meso- to micro-scale descriptions of the complete Phase 3 core is provided in Bradbury et al. (2011). Here we focus on new results from 25 whole-rock core samples and/or cuttings of lithologic/structural units in the near-fault environment including: 1) foliated siltstone-shale with block-in-matrix fabric (Silver and Beutner, 1980); 2) black cataclasite to ultracataclasite fault-related rock; and 3) serpentinite-bearing phyllosilicate-rich fault gouge (Table B1).

For comparison, we also examine micro-scale properties (using petrography/microstructure, SEM, XRD, and XRF) of 22 surface samples collected in the Franciscan Formation (Bailey et al., 1964) near San Simeon, CA (Cowan, 1978; Hsü, 1969) and Goat Rock Beach near Jenner, CA (Figures 4-1 and 4-2). Surface sample localities were chosen based on similarities in composition textures, and structural setting (Table B1; Figures 4-5 and 4-7). Moore and Rymer (2012) also compare a serpentinite-bearing shear zone outcrop, Nelson Creek near the SAFOD drill site, to the SDZ and CDZ rocks and suggest these rocks are sourced from metasomatic alteration and tectonic entrainment of Coast Range Ophiolite within the SAF at depth.

We describe three rock units from the SAFOD core (Table B1), and from the two exhumed sites, in order to: 1) constrain rock properties and structural and permeability architecture within the near-fault environment at ~ 3 km depth; 2) decipher between seismic and aseismic deformation features and potential rates of deformation; and 3)
increase our understanding of the geochemical alteration associated with shearing and evidence for fluid migration/influx during deformation in phyllosilicate-rich rocks. Depths of the samples are expressed in meters measured depth [mMD] of the core, which represents the sample location by the measured drilling depth along the deviated borehole.

Foliated Siltstone-Shale with Block-in-Matrix Fabric

West of the SDZ, a foliated siltstone-shale unit with a scaly clay fabric and block-in-matrix texture (Figures 4-1B, 43A, 4-5A-B) was sampled from ~ 3187.4 m MD to 3192.7 m MD in SAFOD Phase 3 core (Table B1; Suppl. Tables of Bradbury et al., 2011). Southwest of the SDZ, clasts are intensely damaged and commonly distorted to stretched or pinch-and-swell shapes, containing numerous intraclast veins (Table B1). The average clast diameter for this area is 2.35 cm (dMOD after Medley and Goodman, 1994). North of the CDZ contact for ~ 3 m, a sheared siltstone/mudstone unit (Bradbury et al., 2011) with block-in-matrix fabrics is fractured and dissected by abundant mm- to cm- thick calcite veins. Here, several veins exhibit fibrous calcite growth (Figure 4-4E). Damage progressively decreases with increasing distance from the CDZ northeast-bounding slip surface contact, as clasts are noticeably less deformed, and fewer veins are present (see Phase 3 Core Photo Atlas, www.earthscope.org/observatories/safod). From ~ 3300 to 3311 m MD, the average clast diameter for block-in-matrix units increases to 3.7 cm, however, a few blocks of siltstone and sandstone reach up to ~1-2 m in core length and exhibit only minor damage.
Figure 4-S1. a) SDZ Major element whole-rock geochemistry from XRF/ICPMS analyses conducted at WSU. b) CDZ Major element whole-rock geochemistry from XRF/ICPMS analyses conducted at WSU.
Figure 4-S2. Percent carbon, $\delta^{13}$C values, and an example application of the Chemical Index of Alteration (CIA) determined from whole-rock geochemical data (Figure 4-S1) applied to fault-related rocks for: A) the SDZ; and B) the CDZ. Sample preparation conducted at USU with total organic carbon and isotopic analyses completed by Viorel Atudorei at University of New Mexico Analytical Geochemical Laboratory.
Figure 4-2. Mesoscopic textures in SAFOD core as compared to exhumed rocks of the Franciscan Formation. For sample details Appendix B, Table B2-A – B2: A) Block-in-matrix fabric in damaged rocks west of the SDZ; B) Black fault-related rock consists of cataclasite to ultracataclasite; C) Foliated fault gouge in Phase 3 core at 3197.8 m MD; D) E) SAF-related shear zone in Franciscan rocks exposed at Goat Rock State Beach, California; F) Foliated phyllosilicate-rich gouge from shear zone at Goat Rock State Beach, California; and G) Block-in-matrix fabric exposed in sheared Franciscan mélange north of San Simeon State Beach, California.
Figure 4-3. Textures of deformed rocks viewed in thin section. A) Brecciated claystone and cataclasite with fluidized morphologies (ppl); fractures filled with opaque groundmass form boundaries parallel to cataclasite foliation direction and connect to multiple high-angle to perpendicular zones of injected cataclasite (scalebar represents 1 mm) at 3187.5 m MD; B) Alternating fine to ultrafine layers and/or generations of cataclasite and ultracataclasite of the black fault-related rock at 3193.9 m MD suggest repeated slip along localized surfaces; multiple generations of fine carbonate-filled veins offset the groundmass and older veins at high-angles; spherules of pyrite are present within the darker bands of ultracataclasite near the center of the photograph (scalebar represents 1 mm); C) Magnified view of the vein morphology in polarized light provide evidence for both temporal and compositional variations associated with episodic fluid flow; the black opaque mineral in the center of the primarily calcite-filled fracture is pyrite, suggesting reducing conditions within the latest fluid pulse (scalebar represents 0.5 mm); D) Rounded clasts of variable composition entrained within fault-gouge (view is polarized light with gypsum plate inserted); convoluted flow textures surround clasts and numerous clasts exhibit altered rinds, coupled with distorted vein morphology may suggest episodic movement indicative of slow, recurrent aseismic slip with associated fluid interactions; (scalebar represents 1 mm); and E) at 3299.1 m MD multi-layered carbonate vein run parallel to slip surface connects to multiple high-angle veins oriented perpendicular to fracture (see Mittmempergher et al., 2011 for comparison; scalebar represents 0.5 mm).
Figure 4-5. Thin-section photographs of sheared rocks in SAFOD Phase 3 samples shown in the left column versus analog materials shown on the right and sampled from exhumed exposures of Franciscan mélange, central to northern California. Strong similarities exist and suggest SAFOD fault-related rocks have experienced similar processes during deformation and fluid-rock interactions, and/or the SAFOD rocks sampled in the shear zones contain Franciscan protolith. A) Black fault-related rock (Figures 4-1, 4-2) adjacent to the SDZ from SAFOD Phase 3 Core at 3193.6 m MD; B) Black fine-grained rock within exposure of Franciscan mélange sampled near San Simeon, CA; C) Fault gouge associated with SDZ from SAFOD Phase 3 Core 3197.9 m MD; Note alteration rind surrounds clast and contains coating of surrounding groundmass suggesting rotation of clast; note opaque to dark-red, high-relief grain near base of picture (Cr-Spinel; Also refer to Figure 3-7 of Moore and Rymer, 2012); D) Sheared fault gouge from near San Simeon that contains clasts of recycled cataclasite and distinct grains of dark red Cr-spinel, similar in both composition and texture to the SAFOD fault gouge of (c); E) Samples fault gouge at the micro-scale illustrate the distinct pervasively foliated texture associated with the SDZ and CDZ of SAFOD (shown is the SDZ at 3197.7 m MD); Carbon analyses suggests the isolated and darker colored groundmass may be infused with hydrocarbons (Figure 4-S2; Bradbury and Evans, 2010); and F) Sheared phyllosilicate-rich rocks within the Franciscan Formation near Goat Rock, northern CA are nearly identical to the textures shown in (E). Here, a few veins show fibrous calcite growth (Figure 4-3E).
At the micro-scale, the block-in-matrix rock unit is characterized by sedimentary lithic fragments, reworked cataclasite, or clay clast aggregates (Figure 4-3A and 4-5A; Andreani et al., 2010; Boutareaud et al., 2008; 2010) embedded within an internal layering of fine-grained sheared cataclasite bands and foliated scaly clays. Within the cataclasite bands, irregular and discontinuous opaque oxides (primarily magnetite) infill fractures parallel to the foliation direction. Injection-like structures filled with black-ultrafine matrix and cataclasite are oriented at sharp boundaries perpendicular or oblique to the main cataclasite layer (Figure 4-3A). High-resolution SEM images show shear zones dissect at high-angles to the foliation fabric of the matrix and contain well-developed platy clay infilling (Figure 4-6A-B). The clast aggregates (Figure 4-6B) consist of conglobulated clay and/or reworked cataclasite grains that appear to have rotated and flowed between bounding fracture/foliation surfaces, and contain continuous to discontinuous rims of surrounding reworked- and/or altered gouge matrix. Quartz, feldspar, smectitic clays, and magnetite are the primary mineralogical constituents of this rock unit, with Fe-rich sulfides and Mg-oxides disseminated throughout the matrix and locally as fracture infillings.

The XRD results indicate Mg-rich palygorskite clay is also present locally within the fine-grained matrix (Suppl. Tables, Bradbury et al., 2011). For the 12 samples analyzed, silica-concentrations are high southwest of the SDZ, low within the SDZ and CDZ, moderate to high adjacent to the CDZ boundary, and decrease to moderate values east of the CDZ (Figure 4-S1a-b). Southwest of the SDZ boundary, the block-in-matrix rocks are high in silica and locally high in carbonates (likely associated with clasts), with
titanium oxide and iron oxide also present in moderate amounts (Table B1). Total organic carbon (TOC) measurements southwest of the SDZ, between 3187.4 m MD and 3189.3 m MD, averages ~ 1.2 % (Table B1; Figure 4-S2). Northeast of the CDZ, between 3299 - 3301.5 m MD, average TOC increases to ~1.4 %. Values of volatile elements (loss on ignition, LOI) are low relative to the black fault-related rocks to the immediate east and to the SDZ fault gouge (Figure 4-S1).

We apply the Chemical Index of Alteration equation (Nesbitt and Young, 1982) as a proxy for the intensity of chemical alteration across the fault zone, where:

\[
\text{CIA Index} = \frac{\text{Al}_2\text{O}_3}{(\text{Al}_2\text{O}_3 + \text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO})} \times 100.
\]  

(1)

Due to the abundance of clays within the gouge matrix, CIA values are typically moderate to high for the phyllosilicate-rich portion of the block-in-matrix and fault-related rocks (Figure 4-S2). In general, entrained clasts show highly variable compositions (Figure 4-S1) and in general, show exhibit low CIA Index values (Figure 4-S2). Locally, the presence of calcite veins increases the LOI for clasts relative to nearby matrix compositions in addition to the samples analyzed from the SDZ and CDZ.

**Black Ultrafine-Grained Cataclasite**

Near the western edge of the SDZ, ultrafine, cohesive black sheared to black stained fault-related rocks are present from 3192.7 m MD to 3196.3 m MD (Figures 3-3B and 3-4; Bradbury et al., 2011). The black fault-related rock is characterized by
alternating interlayers of cataclasite, variably altered clay, and slight changes in grain size (Figure 4-3B-C). A few samples lack any discernable texture from meso- to micro-scales (Figure 4-4A). Discrete slip surfaces offset the multi-layered zones of fine- to ultra-fine grained cataclasite (Figures 4-2B, 4-4B). Veins filled with calcite and locally pyrite are parallel to or at high-angles to the foliation direction within the fine-grained groundmass (Figures 4-3C and 4-4). Several veins (mm- to cm-thick) contain a visible central fracture interface filled with carbonates, Fe-sulfides and Mg-oxides, suggesting cyclic pulses of fluids with potentially differing redox conditions (Figure 4-3C; Figure 4-4c1, c5, c6). Pyrite framboids are also present as isolated masses within the gouge matrix (Figure 4-6C) and may be related to either diagenesis, hydrothermal alteration, or metasedimentary rocks (Scott et al., 2009). Numerous thin (< mm-thick) carbonate veins trend parallel and at high-angles to the ultrafine comminuted material, and may cross-cut older vein systems (Figure 4-3B). Increases in magnetite abundance is observed at the micro-scale in both the groundmass and concentrated within fracture fillings (Bradbury et al., 2011). Silica-concentrations are moderate within the few samples tested, and show local increases in Na-, Ti-, Al-, and Fe-oxides (Figures 4-4C, 4- S1a-b – 4-S2). The TOC values decrease towards the SDZ boundary with values ranging from ~ 0.4 - 1.1 %. CIA values are moderate to high for this unit (Figure 4 -S2).

Southwest Deforming Zone (SDZ) and Central Deforming Zone (CDZ)

The rocks of the SDZ and CDZ exhibit a non-cohesive scaly clay fabric (Vannucchi et al., 2003) enveloping rounded to lens-shaped clasts of predominately
serpentinite, clay, quartz, reworked cataclasite, or fine-grained altered sedimentary or volcanic lithic clasts of mixed composition (Figure 4-1C-D; Bradbury et al., 2011). The SDZ occurs from ~3197 m MD to 3198 m MD core depth, and the CDZ from ~3296 m MD to ~3299 m MD core depth, corresponding to the low-velocity zones reported by Zoback et al. (2010) in the borehole geophysical logs at ~3192 m MD and ~3302 m MD, respectively.

The complex array of anastomosing surfaces creates the scaly clay fabric and displays self-similarity on all scales. Loose fragments or pieces of fault gouge in the core show polished and slickenlined surfaces are pervasive (Figure 4-1C-D). Petrographic observations (Figures 4-3 and 4-5) reveal anastomosing phyllosilicate-rich seams surround interlayers of fine-cataclasite, rotated or sheared clasts and reworked cataclasite fragments, and/or carbonaceous material.

Mineralogical analyses indicate the fault gouge matrix is predominately composed of saponite with lizardite ± chrysotile and magnetite (Bradbury et al., 2011; Lockner et al., 2011; Moore and Rymer, 2012). Many clasts within the matrix are mantled by an outer rim of clay or contain altered material within the shear tails surrounding the edges (Figure 4-5C, 4-7C). Localized zones of cataclasite and microbreccia support brittle deformation that are in turn, are surrounded by more competent elongated and rotated clasts mantled with clay- or reworked cataclasite with flow features suggestive of ductile or saturated deformation conditions (Figures 4-3, 4-5, 4-6).
Figure 4-6. Scanning Electron Microscope images of SAFOD Phase 3 Core: A) Neominalized clay growth (e.g. Schleichler et al., 2010) within hairline fractures of black fault-related rock at 3187.5 m MD; B) Conglobulated textures between localized slip surfaces within the black fault-related rock (scalebar represents 1 mm) at 3187.5 m MD; C) Pyrite mineralization within fine-grained clayey gouge of the SDZ at 3197.4 m MD; D) Conglobulated fault gouge with disorted vein patterns of the SDZ near 3197.7 m MD (scalebar represents 1 mm) may suggest fluid saturation of fault gouge during shear (also refer to Figure 3-2D); E) rounded, altered, and clay-rimmed clasts embedded within fine-grained groundmass within foliated fault gouge of the SDZ at 3197.9 m MD; and F) Pyrite growth surrounded by isolated irregular zones of carbonaceous material within clay gouge of the CDZ near 3299 m MD. Note, depths are reported as measured core depths and require a depth correction for comparison to geophysical log data (see Zoback et al., 2010).
Figure 4-7. Scanning Electron Microscope images of exhumed shear zones within the Franciscan Formation: A) Pervasive foliated fabric exists to the submicron scale in sample in shear zone within Franciscan Formation near Goat Rock, CA; B) Isolated and altered clasts with varying degrees of roundness appear to “float” within fine- to ultrafine-grained groundmass (see also Figure 4-3F; sample from shear zone within Franciscan Formation near Goat Rock); C) Alteration and/or clay transformation pattern appears to be associated with an interaction between the fracture system and the phacoidal-shaped clast, suggesting extensive fluid-rock reactions at this scale (sample from near Goat Rock, CA); D) Conglobulated texture and alteration of clasts within sheared rock of the Franciscan Formation near San Simeon, CA; E) Pyrite mineralization parallel to foliation direction and fracture surface, shear zone within Franciscan Formation, San Simeon, CA; and F) Spherule of pyrite within groundmass of shear zone within Franciscan Formation, near San Simeon, CA.
Figure 4-4. Back-scattered Scanning Electron Microscope (SEM) images of the black fault-related rock unit at 3193.9 m MD highlight compositional and textural variations at fine-scales: A) Area where few discernable structures are visible and unit appears more massive at this scale; B) Carbonaceous, platy clay particles with well developed crystal structure; C) Fe-sulfide crystallization surrounds fracture surface; EDAX compositional maps show distribution of selected major elements including: c1) Fe; c2) Al; c3) K; c4) Si; c5) S; c6) Mg; and c7) Na.

Calcite veins are generally restricted to the isolated clasts or blocks of serpentine, however, if they are present within fault gouge they typically trend perpendicular to the foliation direction. At the micro-scale, the calcite veins may appear
curvilinear or slightly disrupted (Figure 4-3D). Pyrite mineralization may have
occurred during fluid interactions locally throughout the fault core gouge as evidenced by
the presence of frambooidal growths and spherules in the matrix and euhedral crystals
formed adjacent to and lining numerous fracture surfaces (Figure 4-6C-F). Distinct high-
pressure and/or temperature minerals identified in the matrix and/or clasts include Cr-rich
spinel, Ti- sphene, and andradite garnet (Table B1). These high-pressure minerals may
serve as indicators for the origin of the source protolith (Moore and Rymer, 2012).

Significant fluid-rock interactions for the near-fault environment are suggested by
the presence of Mg- and Fe-rich clays, pyrite, magnetite, carbonaceous material, and
calcite in the fault-related rocks. Other workers have also documented fluid-enhanced
deformation features in the Phase 3 SAFOD core (Gratier et al., 2011; Mittempergher et
al., 2011).

We apply the CIA calculation to the whole-rock geochemical data to test for any
observable patterns in alteration and/or hydration within the SDZ and CDZ relative to the
surrounding rock samples (Figure 4-S2). Individual clasts within the fault gouge show
low CIA values typically associated with unaltered protolith and/or mafic rock
compositions (Nesbitt and Young, 1982). The XRF analyses of samples in both the SDZ
and CDZ show fault gouge increases in FeO and MgO concentrations relative to samples
in the surrounding rocks (Figure 4-S1). The Ni-, Ti-, and Cr-oxide values are also high
within clasts entrained in the fault gouge and locally as individual grains within the
matrix. Cr-spinel and andradite garnet were identified in thin-section (Bradbury et al.,
2011; Moore and Rymer, 2009, 2012) and contain these elemental constituents. In the
CDZ, one sample measurement shows an apparent decrease of TOC to 0.4. The LOI values are locally high within the fault gouge material and support the presence of organic carbon (Ball, 1964) or significant hydration and alteration (Schulz and Evans, 2000).

Natural Surface Analogs to SAFOD Fault-related rocks

Comparison of fault-related rocks from SAFOD to samples collected within exposed and sheared lenses of serpentinite-bearing matrix mélanges within the Franciscan Formation near San Simeon and Goat Rock Beach, California (Figures 4-1, 4-5, and 4-7) indicate that they are texturally analogous and similar in composition. For example, near San Simeon, CA (Figure 4-1, 4-2F-G) black ultrafine rocks with fluidized geometries are found in narrow (cm-to m-wide) shear zones surrounded by a serpentinite-bearing block-in-matrix mélange. The black rocks are similar in composition and texture to the black fault-related rock unit sampled in SAFOD Phase 3 Core (Table B1) whereas, the surrounding foliated serpentinite-bearing scaly clay matrix compares to the fault gouge of the SDZ and CDZ (Figures 4-2C-D and 4-5).

At the San Simeon site, the rocks are moderately to strongly lithified relative to the non-cohesive nature of the SAFOD core, however, at finer scales, the structures are nearly identical (Figures 4-5 – 4-7). Surface outcrops of non-cohesive scaly clay gouge similar to the Phase 3 core fault-related rocks have also been documented in a block of serpentinite entrained within a more recently active shear zone associated with the SAF at
Nelson Creek, ~ 2.4 km north-northeast of the SAFOD site (Moore and Rymer, 2009, 2012).

Fault-related rocks from the SDZ (Figure 4-5C) and CDZ (Figure 4-5E) exhibit evidence for both brittle and distributed deformation at the micro-scale. Evidence for brittle deformation includes the presence of broken grains, reworked cataclasite fragments (Figure 4-5E), and discrete microfractures (Figures 4-3D-E). Flow-like morphologies, block-in-matrix fabrics, and S-C fabrics in the fault gouge all support an interpretation of distributed deformation within these zones (Figures 4-3D-E; Figures 4-5C, E). Samples from the CDZ (Figure 4-5E) and Goat Rock Beach (Figure 4-5F) highlight the complex anastomosing network of slip surfaces created by repeated deformation in phyllosilicate-rich rocks and may be an indicator of deformation by aseismic creep and/or microseismicity. This fabric is also identified in SEM images of thin-sections for samples from the SDZ (Figure 4-3D) and Goat Rock Beach (Figures 4-7A-C).

Sheared mélange samples from San Simeon (Figure 4-5D) and Goat Rock Beach (Figure 3-5F) exhibit similar textural features as those characterized in the SDZ and CDZ rock samples from SAFOD Phase 3 core (Bradbury et al., 2011; Gratier et al., 2011; oldsworth et al., 2011). Sheared melange matrix from near San Simeon also contain clasts of recycled cataclasite (Figure 4-4E) and distinct grains of dark red Cr-spinel, pyrite frambooids and spherules, similar mineralogies as to those observed in both the SDZ and CDZ fault gouges (Figures 3-6C; 3-6F; 3-7F).
Discussion

Numerous hypotheses have been proposed to explain aseismic creep and the weak mechanical behavior of the central segment of the SAF at SAFOD, and a range of work has examined portions of the SAFOD core. Based on this work, these hypotheses include: 1) the presence of frictionally weak minerals within clay gouge such as talc and/or serpentineite (Carpenter et al., 2009; Lockner et al., 2011); 2) the presence of high density of smectite-rich coatings (<100 nm thick) on fracture surfaces interconnected at low angles (Schleicher et al., 2010, 2012); 3) pressure solution creep (Gratier et al., 2011); 4) transient migration of fluids into the fault zone (Hickman et al., 2004; Mittempherger et al., 2011; Wang, 2010); 5) crush-origin pseudotachylytes (amorphous phases) within fault-related rocks (Janssen et al., 2010); and 6) foliated fault gouge fabrics (Colletini et al. 2009; Niemeijer et al., 2010). Our analyses of the SAFOD Phase 3 core fault-related rock shows the actively creeping SAF at ~ 3 km depth records a complex interplay of processes and fluid-rock interactions that evolve in both space and time (Table B1; Figures 4-3 – 4-6).

The SDZ and CDZ fault strands are separated by over 100 m in the SAFOD borehole, but they share distinct mineralogical, textural, and geophysical signatures (Figures 4-3 – 4-6; Figures 4-S1 – 4-S2; Bradbury et al., 2011; Carpenter et al., 2011; Lockner et al., 2011; Zoback et al., 2010), suggesting similar modes of formation. These fault strands are possibly linked at depth to form an anastomosing array of splay faults separated by fault slivers or lenses of more competent and/or less-deformed rocks.
(including serpentinite, sedimentary and volcanic rocks) in the shallow crust intersected the borehole.

Block-in-matrix rock units adjacent to the active fault strands record an apparent damage asymmetry of the active fault zone. Near-fault damage is more intense on the southwest side of the SDZ and average clast sizes are smaller compared to the area sampled to the northeast of the CDZ (Table B1; Table B4), suggesting extensive grain comminution processes and/or granular flow (Chester et al., 1993; Sibson, 1977). Measurements of casing deformation support an active asymmetry within the fault zone as creep is more pronounced in the CDZ relative to the SDZ (Jeppson et al., 2010; Zoback et al., 2010). Southwest of the SDZ, microstructures and fabric within the block-in-matrix and black fault-related rock units display evidence for localized and distributed deformation (Table B1; Figures 4-3 - 4-5). Injection of granular material into surrounding matrix (Figure 4-3A) may occur in response to increased fluid pressures and hydraulic fracturing (Ujiie et al., 2007). From southwest to northeast across the SAF, following the deformation trend, the alteration pattern observed in the available samples is higher southwest of the SDZ and lower between the SDZ and CDZ, returning to higher values east of the CDZ trace (Figure 4-S2). Several clasts within the fault gouges have very low CIA values (Figure 4-S2) relative to all other samples. (These values may be biased due to the abundance of carbonate veins within some of the clasts.) Fibrous calcite veins northeast of the CDZ and numerous micro-veins southwest of the SDZ (Table B1; Bradbury et al., 2011) suggest that localized fluid pressure changes occurred along the shear zone boundaries. The abundance and clustering of veins, coupled with
sulfide and iron-oxide mineralization, and increases in TOC (Table B1; Figure 4-S2), are evidence for potential interactions with redox and/or hydrocarbon–bearing fluids during shearing (Cobbold and Rodrigues, 2007; Rodrigues et al., 2009).

Damage elements associated with seismic slip and co-seismic fluid infiltration observed in the black sheared to black stained fault-related rocks, include: slip localization, cataclasite, and intense microfracturing and numerous cross-cutting veins. Evidence for repeated deformation in these rocks is suggested by the presence of multiple layers of cataclasite and reworked cataclasite clasts. Similar black-stained intervals are also present locally in the block-in-matrix unit to the southwest of the SDZ, but they do not appear to extend or become incorporated into the adjacent SDZ gouge. The TOC analyses indicate at least some of this staining is rich in organic carbon, and locally reaches petroliferous grades (Table B1; Figure 4-S2; Peters and Cassa, 1994) supporting the interpretation that some migration of hydrocarbon-bearing fluids from Great Valley sediments (?) has occurred along the fault zone (Bradbury et al., 2011). The black staining with injection-like morphology coupled with multi-phase calcite veins indicates that fluid-assisted processes that may also contribute to mobilization of hydrocarbons and other fluids (liquids and/or gas) by transient changes in pore fluid pressure during slip (Holdsworth et al., 2011; Mittempherger et al., 2011; Rowe et al., 2009). The presence of carbonaceous residues (Figure 4-S2) and the strong petroliferous odor of the SAFOD core when opened in core runs indicate the presence of hydrocarbons within the SAF at depth could also assist in altering the fault and be a major factor contributing to fault zone weakness and/or increased chemical-rock reactions in the presence of associated fluids
(e.g. Colletini et al., 2011). Wiersberg and Erzinger (2011) document the presence of methane within the fault zone, and Henyey et al. (2011) indicate that within the fault zone, natural gas and saline formation waters are present.

Within the shear zones of the SDZ and CDZ (Figures 4-S1 – 4-S2), the intensity of distributed deformation features such as S-C fabrics, clay alteration, and concentrations of Fe-Mg oxides and sulfides all increase relative to the protolith. Distinct flow-like fabrics and conglobulated textures occur locally throughout all phyllosilicate-rich fault-related rock units and support an interpretation that distributed (aseismic) deformation or possibly fluid-saturated and/or influenced deformation within the fault zone. Clay-rimmed clasts, foliated fabrics, and conglobulated textures are associated with fluidization-type processes and shearing and may be accommodated by distributed strain (Fagereng and Sibson, 2010) within the phyllosilicate-rich rocks. Thin-section and SEM images also suggest the stronger blocks and clasts rotated in an irregular, fluidized manner (Figures 4-5 – 4-6) throughout the gouge matrix. This is consistent with textures associated with distributed deformation and slip (Fagereng and Sibson, 2010). Clay-rimmed clast coatings and the clay-infilling between blocks or fragments are also features associated with fluid-related processes (Boutaread et al., 2010; Rowe et al., 2009).

Geochemical analyses (Figure 4-S1) indicates a sharp increase in Mg- and Fe-oxide as silica content decreases. This trend is due to the presence of smectite (saponite) in the scaly clay fault gouge (Bradbury et al., 2011; Lockner et al., 2011; Moore and Rymer, 2010, 2012). The Mg- and Fe-rich saponite has an extremely low coefficient of friction ($\mu \approx 0.15 – 0.21$) in laboratory studies and exhibits stable-sliding frictional behavior
(Carpenter et al., 2009; 2011; Lockner et al., 2011). Saponite is commonly an alteration product of serpentine (Brearley, 2006; Zolensky et al., 1993). Lizardite ± chrysotile compositions were identified in XRD and SEM (Bradbury et al., 2011; Moore and Rymer, 2007, 2012; Morrow et al., 2010; Solum et al., 2007), and in thin-section, with the grains are often in association with magnetite and Ni-oxides and several distinctive minerals within both the SDZ and CDZ fault gouge matrix (Table B1; Moore and Rymer, 2012). These alteration products suggest fluids play an effective role of mobilizing and concentrating elements within the fault zone at the grain and slip-surface scale (Micklethwaite et al, 2010). The CIA index ranges from low to moderate for the SDZ and CDZ but this result may be a function of the abundance of Mg- and Fe-rich clay in the gouge matrix rather than Al and the abundance of relatively unaltered clasts. The LOI values may also be useful as an indicator for fluid assisted alteration (Schulz and Evans, 1998). Results for the samples tested show LOI is greatest in the CDZ region (Figure 4-S1), and a positive correlation to higher TOC values is also observed (Table B1; Figure 4-S2).

The extent of spatial variation in composition and textures from the micro- to submicron-scale (Figures 4-2 – 4-6; 4-S1 –4-S2) across the SAF in SAFOD supports the interpretation of mixed styles of deformation (Fagereng and Sibson, 2010) or multiple deformation events and supports an the idea of an evolving structural and permeability architecture that changes in space and time. In situ sampling across the SAF at ~ 3 km depth at SAFOD demonstrates that the fault zone exhibits wide zones of pervasive deformation (~10-15 m) separated by thin, anastomosing (~1-2 m) foliated gouge zones
(SDZ and CDZ), numerous discrete slip surfaces (mm-cm thick) and a few entrained blocks (~1-2 m in core length) that are only weakly deformed. These textures create a structural fabric that implies deformation processes related to aseismic creep and stable frictional sliding (Colletini et al., 2009; Faulkner et al., 2003) with periodic seismic events. The presence of saponite coupled with the potential for a periodic influx of hydrocarbons within the active shear zones may contribute to the formation of textures that promote additional weakening and aseismic deformation of the SAF.

Enhanced permeability parallel to strike and reduced permeability perpendicular to the fault strands was documented in mud-gas analyses at SAFOD (Wiersberg and Erzinger, 2011). Based on the presence of serpentinite and higher-temperature mineral assemblages, Moore and Rymer (2012) and Lockner et al. (2011) also hypothesize that serpentinite is channelized up along the fault zone from depth and influences metasomatic reactions within the fault. This buoyancy driven origin requires a source of fluids at depth and extensive physio-chemical interactions to bring material from depth. Similar fluid-assisted processes of transporting serpentinite-bearing rocks from depth have been documented in flow mélanges of the Franciscan Formation (Cloos, 1984) or through volumetric expansion associated with serpentinization (Page et al., 1999; Shervais et al., 2011). The foliated block-in-matrix units juxtaposed against lenses of serpentinite-bearing fault gouge and serpentinite through repeated shearing, fragmentation, and preferential mixing of serpentinite lenses within Franciscan mélange along the SAF similar to the outcrops at Goat Rock and San Simeon (e.g. Allen, 1968; Irwin and Barnes, 1975). Alternatively, these fault-related rocks may represent slivers of
Coast Range Ophiolite that have migrated upwards from depth along the SAF (Moore and Rymer, 2012).

Mélange fabrics form through a variety of depositional and post-lithification processes, including tectonic folding and faulting, sedimentary and slope failure processes, and origin by vertically driven movements related to diapiric and/or volume expansion processes (Bailey et al., 1964; Festa et al., 2010; Raymond, 1984; Shervais et al., 2011; Silver and Beutner, 1980; Vannucchi et al., 2003; Wakabayashi and Dilek, 2011). Each process is associated with distinct rock textures and/or compositions that may reflect styles of deformation (Cowan, 1985; Raymond, 1984; Vannucchi et al., 2003).

Both the SAFOD fault-related rocks and analog samples (Figure 4-6) share similar features such as: 1) block-in-matrix textures and scaly clay fabrics characterized by S-C surfaces; 2) sheared serpentinite clasts and blocks; 3) multiple phases and styles of calcite veining (Figures 4-3D-E); 3) pyrite mineralization (aligned within interlayered fractures and as isolated framboïds within the matrix (Figures 4-3 and 4-6); 4) fluidized and conglobulated textures structures zones; and 5) alteration-rims surrounding numerous clasts entrained within the gouge or matrix materials (Figure 4-5C). All samples demonstrate a pattern for extensive fluid-rock interactions.

Conclusions

Whole-rock core from the creeping segment of the SAF at SAFOD provide insight into the mineralogical composition, geochemical alteration, and rock textures associated with active aseismic creep and the conditions that influence deformation and
fluid (liquid and/or gas) interactions along the fault within the shallow crust.

Serpentinite, fine-grained foliated phyllosilicate-rich fault gouge, mineralization, and carbonaceous material are all present within the fault zone at SAFOD, and may explain why aseismic creep occurs along the central segment of the SAF. Slow slip may develop as a result of pore fluid exchange and the alteration of frictional properties of the materials within the fault (Knipe, 1993; Rudnicki and Rice, 2006) however, high fluid pressures are not necessarily required during deformation. The SAFOD core exhibits characteristics of rocks that have experienced high-pore fluid pressures during their development history, however, this cannot be definitively attributed to active slip, however, the inherent textures may contribute to an aseismic deformation style. The SAFOD core does show that deformation within the active SAF at depth is highly variable spatially and temporally over relatively finite distances. Direct sampling and analyses of SAFOD core reveals the SAF structure at depth and provides constraints on the physical and chemical processes and tectonic history associated with active SAF deformation.

References


CHAPTER 5

ROCK PROPERTIES OF THE SAN ANDREAS FAULT IN THE SHALLOW CRUST
FROM BOREHOLE GEOPHYSICAL LOGS AT SAFOD

Abstract

We evaluate the borehole geophysical data and calculate elastic modulii for lithologic and structural units identified in SAFOD Phase 3 core and relate these data to the structural and/or permeability architecture, and overall fault zone deformation behavior in the shallow crust. We document the presence of distinct signatures of geophysical data that correlate to either major structural boundaries or fine-scale compositional or textural variabilities within the fault zone.

Highly reduced velocity and elastic modulii surround the SDZ and CDZ, the Buzzard Canyon fault to the southwest, and within another bounding fault to the northeast. At the finer scale, rock properties are highly variable over small distances within the borehole, suggesting complex fault zone architecture as documented by studies of fault zone petrology and reflected in physical properties.

Introduction

The relationships between geophysical wireline logging data and geologic data within the SAFOD borehole (Jeppson et al., 2010) provide critical information with

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respect to in situ rock properties and have implications related to fault zone mechanical behavior. Due to challenges associated with drilling into and collecting in situ data of active fault zones, physical rock properties are commonly predicted or inferred through theoretical or empirical relationships (Karacan, 2009), geophysical inversion (Ben-Zion, 1998; Ben-Zion et al., 2003; Li et al., 2004), or extrapolated from laboratory experiments and/or from field studies of exhumed faults (Carpenter et al., 2009; Faulkner et al., 2006; Ikari et al., 2009; Worthington and Hudson, 2000). A fundamental underlying assumption is that lithologic and fault-related rock units are characterized by their physical properties as measured through various geophysical tools (Bedrosian et al., 2007).

We present results of research that examines the physical properties of SAF fault-related rocks with an aim to understand the nature of the constituent properties in the near-fault environment and the state of stress within the SAF at shallow crustal levels (Jeppson et al., 2010; Tembe et al., 2009). Integration of geologic and borehole geophysical data provides constraints on the subsurface structure and fault zone behavior at SAFOD, where the fault deforms through aseismic creep or stable frictional sliding at shallow crustal levels (Zoback et al., 2010). Jeppson et al. (2010) note that accurate in situ measurements of fault zone properties are important for estimating several key factors that may influence earthquake generation and absorption of earthquake energy, including:

1) How seismic energy travels and is attenuated in fault zones (Ben-Zion, 1998; Li and Vidale, 2001) and the amount of energy available for other
physio-chemical processes (e.g. thermal pressurization) in the near-fault environment (Abercrombie et al., 2006; Boullier et al., 2009; Brodsky and Kanomori, 2001; Han et al., 2007; Shipton et al., 2006)

2) Spatial and temporal variations in rock properties and structure over the seismic cycle (Brenguier et al., 2008; Li and Vidale, 2001)

3) Pore fluid pressures and fluid flow mechanisms (Shipton et al., 2006; Caine et al., 2010)

In this paper, we evaluate the borehole geophysical data (sonic velocity, resistivity, density) to calculate elastic moduli for lithologic and structural units identified in SAFOD Phase 3 core (Bradbury et al., 2011) and relate these data to the structural and/or permeability architecture, and overall fault zone deformation behavior, in the shallow crust at this location.

Methods

In order to determine the relationships between rock properties and geophysical properties, we explore the data sets visually with 3-D graphical methods and by tabulation of average property values as measured via downhole logging techniques in the SAFOD borehole for each lithologic unit described in Bradbury et al. (2011). In this paper, we focus primarily on the geophysical properties that can be directly correlated to rock composition, deformation behavior, and permeability architecture (e.g. velocity, resistivity, and density measurements) and rock strength (elastic moduli).
Geophysical open-hole log data were collected at the SAFOD drill hole during all phases of drilling and are available through the Earthscope and ICDP data systems (www.safod.icdp-online.org). The source data utilized in this project is: SAFOD-MH Open Hole Downhole Logging Baker Atlas [Aug 11 2005 11:00PM Aug 12 2005 7:40AM ] Baker Atlas File BM0001; the depth range is listed as: 3048 - 3965.46 m.

Whole-rock core is available for only about ~ 4% of this interval between. A complete version of the logged data set used in this work is provided in Appendix C1-C5.

Geophysical borehole measurements were made every 15.25 cm and the data sets include both discrete and smoothed or averaged measurements. Our primary data sets are the logs over the interval of 3000 to 4000 m measured depth, which includes the arkosic sandstones and silty shales (Jeppson et al., 2010; Springer et al., 2009) southwest of the Southwest Deforming Zone (SDZ after Zoback et al., 2010); block-in-matrix units and foliated clay gouge adjacent to and within the SDZ and Central Deforming Zone (CDZ after Zoback et al., 2010), and the sheared siltstones, shales, and fine-grained sedimentary rocks northeast of the CDZ (Figure 5-1; Bradbury et al., 2011).

To align the measured driller’s depth of Phase 3 whole-rock core to the geophysical logging data, a correction is required due to an observed offset between the location of the distinctively low total natural gamma signatures within the SDZ and CDZ relative to the reported measured core depths (Zoback et al., 2010). For the SDZ 5.03 m is subtracted from the depths in the logging data to correlate to the measured core depths; whereas for the CDZ, 3.96 m is added to the logging data for comparison to measured core depth intervals.
We present velocity measurement data for every 0.5 meters as recorded in the SAFOD borehole (Appendix C4) based on a 3 m moving average for Phase 1, a 2 m moving average for Phase 2 (Jeppson et al., 2010), or the non-averaged data. Due to compositional and textural variability at the meso- to micro-scale identified in Phase 3 core by Bradbury et al. (2011), the calculated averages for each lithologic and/or structural unit over the 41 m of core are based on the non-averaged data (Appendix C4). Elastic modulii (including shear modulus, Lame’s constant, Young’s Modulus, and Poisson’s Ratio) were calculated for ~ 7000 point measurements based on depth in the SAFOD borehole (Appendix C2).
Figure 5-1. Plot of Geophysical logs ($V_p$, $V_s$, porosity) for SAFOD Phase 3 coring intervals. Black bars represent locations of core and the generalized lithologic and structural units identified in Bradbury et al. (2010). Red shading highlights the low-velocity signatures. Each low-velocity zone is associated with an increase in porosity and within the core contains sheared black shale or serpentinite-bearing, scaly clay fault gouge.
Results

Detailed review of geophysical properties within the near-fault environment of the SAF near ~ 3 km depth suggests that fine-scale variability of composition and structure can be correlated to a distinct set of rock properties. Jeppson et al. (2010) calculated the elastic modulii of the rocks within the SAFOD borehole from the sonic velocity logs and showed that Young’s modulus is significantly lower in SDZ and CDZ compared to the surrounding rocks. There is a wide range of spatial variability of shear modulus within the borehole (Figure 5-2), with significant shifts to highly reduced modulii adjacent to and within the SDZ and CDZ (Figure 5-3). The SDZ and CDZ are the active fault strands of the central creeping segment of the SAF and consist of foliated fault gouge and serpentinite (Bradbury et al., 2011; Zoback et al., 2010, 2011). To evaluate the presence of broader-scale patterns resulting from regional structures surrounding the SAFOD site (Figure 5-3; Appendix C4) and to reduce fine-scale variability associated with downhole measurements, we first averaged the modulii data over 100 m intervals (Figure 5-4; Appendix C, Table C4).

We calculate the elastic properties for each lithologic/structural unit as identified in SAFOD Phase 3 core based on detailed core logging and sampling (Bradbury et al., 2011). The elastic modulii are obtained from the velocities of compressional ($V_p$) and shear waves ($V_s$) determined from full wave sonic logs (Jeppson et al, 2010; Karacan, 2009; Kramer, 1996). Lame’s constant ($\lambda$) and the shear modulus ($\mu$) were calculated from
\[ V_S = \sqrt{\frac{\lambda}{\rho}} \]  

(1)

and

\[ V_P = \sqrt{\frac{K + \frac{4}{3} \mu}{\rho}} = \sqrt{\frac{\lambda + 2 \mu}{\rho}} \]  

(2)

where \( V_S \) is the S-wave velocity, \( V_P \) is the P-wave velocity, \( \rho \) is the density, and \( K \) is the bulk modulus. Using \( \lambda \) and \( \mu \), Young’s modulus (E) and Poisson’s ratio (\( \nu \)) are calculated as

\[ E = \frac{\mu(3 \lambda + 2 \mu)}{\lambda + \mu} \]  

(3)

and

\[ \nu = \frac{\lambda}{2(\lambda + \mu)} \]  

(4)

Figure 5-2. Plot of Shear modulus vs. depth calculated from the sonic velocity data. Significant reductions in the shear modulus are noted at ~ 3192 m (Southwest Deformation Zone - SDZ); 3302 m (Central Deforming Zone); and ~ 3315 m (North-Bounding Fault – NBF – after Thurber, pers. comm., 2011). Whole-rock core and cuttings analyses show a clear link between a significant decrease in modulii and the presence of serpentinite.
Figure 5-3. Elastic modulii data averaged over 100 m intervals. At this scale, fine-scale variations are smoothed and the major shifts in modulii are apparent. At 2100 m, the large decrease in modulii is associated with the tectonic Plate Boundary. Significant shifts are also observed associated with the SDZ, CDZ, and NBF.

The input data and calculated results from this exercise are included in Tables C1 and C3 of Appendix C. Our results using the corrected depth adjustments of Zoback et al. (2010) show that from the 0.5- to 2 m-scale, the Shear and Young’s modulus values for the black fault-related rocks, and the SDZ and CDZ, are actually slightly higher than the immediately bounding rock units (Table C1, C3). A more detailed analyses is required to identify the cause of this finer-scale variability.
Figure 5-4. Three-dimensional plot of velocity, resistivity, and density data using the M2R3-Resistivity data set representing a measurement area of 30-inches outwards from the borehole. The interesting shape shows no obvious correlations and is likely related to averaging methods for the data.

Three-dimensional cross-plotting of velocity ($V_P$), density, and resistivity data is also conducted between 3048 to 3353 m MD in an attempt to delineate fine-scale patterns within rock properties near the SDZ and CDZ (Figure 5-5; Tables C3, C5). If we can define the most representative rock properties based on geophysical data for sections of the borehole where whole-rock core is available, then it may be possible to estimate the nature of the rock with less uncertainty in areas where core is not available.

Resistivity data is available at various depths of inspection (DOI) beyond the borehole wall. At SAFOD, the DOI ranges from 0 in to > 90 in beyond the borehole wall. The larger the DOI number the least likely the value will be influenced by drilling disturbance and thus, may be more representative of formational properties. We chose the M2R6 (60-inch radius) data as a first-step pass to test this three-dimensional cross-
plotting method. The velocity is measured in km/sec and the bulk density data is measured in (g/cm$^3$) from average neutron porosity. Resistivity data is plotted as the Log 10 of (Ω*m). The initial results from using a 3D-plotting function in MATLAB, offers no discernible trends due to the spiral-type shape of the plot (Figure 5-4). This shape is likely a function of the length of the distance used to average the data, which in the available data set, varied between different parameters. However, if the non-averaged data is plotted distinct spatial clustering of the data is easily discerned during rotation of the graph in MATLAB. Using this tool, three main clusters are identified for this plot of velocity, density and resistivity values (Figures 5-5). The distribution of the values for each spatial cluster is defined by visually picking the values from the x, y, and z axes, for density, resistivity, and velocity, respectively. The range of values delineated for a specific cluster are identified to avoid any overlap between clusters. Minor overlap did occur for the density variable as little variation exists between the lithologic units. Next, this range of values for each particular cluster was input into a MATLAB script to match specific cluster properties to depth locations within the SAFOD borehole (Appendix C6).

Results for the frequency of data points that characterize a particular cluster and the depths at which these occur are also shown in Figure 5-5. Cluster 1 is the most prominent set of all cluster groups and occurs throughout the other DOI data sets as well. The depth range for rocks with Cluster 1 properties (Figure 5-5) falls between ~ 3190 – 3340 m MD and correlates to the SDZ, CDZ, and potentially a northern-bounding fault (NBF; Figures 5-3 and 5-5).
Figure 5-5. A) An example graph of cluster analyses for velocity, resistivity, and density data. To identify clusters, the plot is rotated in MATLAB and the lasso the regions of high-density or clustered data. In this example, 3 main clusters are defined on the basis of the range of geophysical properties (velocity, resistivity, and density). From here, using a forloop MATLAB script and the range of cluster properties for each cluster, the depth intervals for each main cluster are generated and shown in a color code that is then correlated back to the depths and representative of whole rock core sampled at SAFOD (B).
Interpretations

Integrated geologic and geophysical data show at the broader scale the elastic moduli are significantly reduced at several locations associated with deformation identified in the SAFOD borehole (Bradbury et al., 2007, 2011; Jeppson et al., 2010; Springer et al., 2009).

Measurements of \textit{in situ} elastic moduli at SAFOD can be used to characterize deformation in the shallow crust and may provide useful constraints for geophysical models. For example, Fialko et al. (2002) suggest decreases in effective shear moduli occurs within km-wide fault zones and indicates these properties are distinct from surrounding crustal rocks. However, most values for elastic modulii are derived empirically and not truly representative of the rock properties at depth. Numerous models (Li and Malin, 2008; Roecker et al., 2004; Thurber et al., 2004; Unsworth et al., 1997) show a zone 200 m to 1 km wide of damaged rock extending to depths between 3-5 km surrounds the SAF at the SAFOD site. Based on our integrated observations from the core-scale to the borehole scale (Bradbury et al., 2010; Jeppson et al., 2010), we suggest this region of damage is at least 300 m wide and possibly up to 1 km (Figure 5-3) and is comprised of anastomosing fault slivers interlayered with a series of elongated blocks (e.g. Faulkner et al., 2003). The damaged region surrounding the fault and lithologic relationships may suggest a type of positive flower structure with various branching faults in the shallow crust, that taper at depth (Harding, 1985; Li and Malin, 2008). These observations support previous geophysical models and interpretations (Li and Malin, 2008; Simpson et al., 2006) that have suggested a positive flower structure for the
SAF, with a complex sinuous geometry at the surface that becomes localized to a narrow region at depth. Such geometries could evolve through repeated deformation within broader zones of compliant materials (reduced elastic properties) at shallower depths, and less compliant sequences at depth (e.g. Fialko, 2004).

At the broader scale, we observe a significant reduction of elastic moduli, especially within the northeast block of the SAF suggesting that the SAF at SAFOD may act as a compliant fault zone (Cochran et al., 2009; Fialko et al., 2002, 2006). This interpretation is consistent with the extensive damage documented throughout the borehole, and the chaotic juxtaposition of intensely sheared to relatively un-deformed blocks throughout the inclined depths of the SAFOD borehole.

Heterogeneous fault zone architecture results in contrasting elastic properties comprised of both velocity weakening and velocity strengthening materials. The presence of a fault zone with such significant variations in elastic moduli also has several implications for fault structure at depth. Some workers have suggested that moduli variations continue to depths of greater than 5 km where the faults structure may act to trap or guides seismic waves (e.g., Li and Malin, 2008), whereas others (Fohrmann et al., 2004) indicate this is a relatively shallow phenomenon. It is important to identify these regions of low velocity and reduced elastic properties in the shallow crust as they can trap seismic energy leading to large motion amplification in their surrounding environment (Fialko, 2004; Fialko et al., 2002).

The elastic properties and hence strength of a fault zone may vary in space and time related to composition, texture, and/or porosity (Song et al., 2004). Stresses may
also vary to produce time-dependent weakening of a particular fault. The presence of microseismicity near SAFOD supports compositional heterogeneities extending below the borehole with rocks exhibiting both velocity-strengthening and velocity-weakening behavior (Wibberley, 2007). The causes of weak fault behavior along the SAF are still under debate with numerous hypotheses proposed for this behavior, such as: mineralogy and frictional properties (Carpenter et al., 2009; Lockner et al., 2011; Moore and Rymer, 2007; Tembe et al., 2006) foliation and fabric-induced weakness (Colletini et al., 2009; Neijemer et al., 2010), clay fracture surface coatings (Schleichler et al., 2010) transient fluid overpressures (Mittempherger et al., 2011; Wang, 2010), geochemical reactions, dissolution precipitation, and reaction weakening (Gratier et al. 2011; Rybacki et al., 2010).

Understanding the complex interplay of physical and chemical processes and varying rock properties within the near-fault environment at SAFOD provides information on the deformation mechanisms that are potentially active during slip along a major plate-bounding fault. Detailed constraints on the structural and compositional variation of material properties are required to decipher these processes (Shipton et al., 2006). In this study we provide direct in situ measurements of rock properties and elastic moduli of the SAF at SAFOD and present representative values for the frictional properties of the SAF in the shallow crust which may be utilized in future geologic and geophysical models of the overall mechanical behavior of the fault zone at SAFOD.
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CHAPTER 6

CONCLUSIONS

From 2002-2007, the SAFOD (San Andreas Fault Observatory at Depth) Scientific Drilling Project north of Parkfield, CA sampled rock in four phases (Hickman et al., 2004, 2007; Zoback et al., 2010, 2011; http://www.earthscope.org/observatories/safod):

1) The Pilot Hole: a separate 2.2 km deep vertical test borehole; 2) Phase One: rock cuttings and downhole geophysical logs from the 0 – 2 km deep vertical SAFOD borehole on the Pacific plate; 3) Phase Two SAFOD main borehole: rock cuttings, spot core, and downhole geophysical logs between ~2-4 km depth in a 55° inclined borehole that extended from the Pacific Plate, northeast into and across the San Andreas Fault transform plate boundary, and into the North American plate; and 4) Phase Three SAFOD main borehole: whole-rock core was sampled from several multilateral holes drilled off of the main SAFOD borehole at ~ 3 km depth where two zones of casing deformation and active creep were targeted.

A main goal of the SAFOD project is to characterize the composition and structure of the San Andreas fault zone and to address questions concerning the chemical and physical processes associated with active deformation. Within the vicinity of SAFOD, active deformation occurs primarily as aseismic creep and repeating microearthquakes (Zoback et al., 2010). In situ sampling and laboratory analysis of SAFOD rocks thus provides an opportunity to examine the nature of an active fault zone undergoing shear and/or creep and to identify features associated with the this process.

This dissertation focuses on identifying the composition, internal structure, and
permeability architecture of the fault zone at SAFOD (Chapters 2-4) and to link the geological characteristics to geochemical alteration (Chapter 2-4) and geophysical rock properties (Chapter 5). Results from point-counting and microstructural analyses of thin sections of Phase 1 & 2 cuttings (Chapter 2 or Bradbury et al., 2007) provide an overview of the lithological and structural setting in the subsurface at SAFOD. At least 6 highly-damaged intervals and/or fault strands are identified based on the abundance of cataclasite and microstructural deformation features are represent several sheared intervals within the main SAFOD borehole. Areas of increased alteration also correlate to regions of damage and support cyclic fluid-interaction and changes in permeability throughout the borehole. A conceptual model for the geologic setting in which the target earthquakes occur is developed was useful to provide constraints on the design and coring of the active San Andreas Fault zone or Phase 3 of SAFOD in 2007.

Detailed characterization of the whole rock core sampled in Phase 3 is presented in Chapter 3 and published as Bradbury et al. (2011). In Chapters 3 and 4, we delineate the composition and structure of the SAF at SAFOD. Results show the SAF consists of broad zone of variable damage (> 300 m wide) that surrounds multiple narrower zones of highly sheared and altered rock containing complex internal structures from the m- to µm scale. Zoback et al. (2010) identified the key fault deformation zones at depth: the southwest deforming zone (SDZ) and the central deforming zone (CDZ). We reveal that fault-related rocks within or adjacent to the SDZ and CDZ contain serpentinite and abundant evidence for both brittle and distributed deformation coupled with variations in fluid-rock interactions. The SDZ and CDZ core materials display highly sheared, foliated
gouge textures with serpentine- and smectite-bearing clay gouge compositions and significant enrichment in Mg-rich clays, and Ni- and Cr-oxides. The SDZ and CDZ rocks show distinct increases in carbonaceous content relative to the surrounding rocks. The northeastern boundary of the CDZ exhibits extensive veining and increases in magnetite and iron-sulfide. Further to the northeast, fault-related damage and alteration continues but follows an overall decreasing trend with greater depth or further northeast into the North American Plate (Bradbury et al., 2011).

In Chapter 5 the relationship between geophysical logging data, rock properties, and geologic data within the SAFOD borehole is explored. Calculations of elastic modulii from geophysical logs verify that the near-fault environment of the SAF at SAFOD is a zone of reduced velocity and decreased elastic modulii at the broader scale but at the finer-scale (meter to sub-meter) these properties are highly variable and may affect the frictional properties and mechanical behavior of the fault.

The physical properties of an active fault zone are difficult to observe in situ, and/or elastic properties are inferred based on assumptions of rock properties at depth or from field studies of exhumed faults (Carpenter et al., 2009; Faulkner et al., 2006; Ikari et al., 2009); estimated by geophysical inversion (Ben-Zion and Sammis, 2003; Ben-Zion et al., 2003; Li et al., 2004, 2007); or extrapolated from experimental methods. Many of these studies indicate that faults comprise zones of reduced seismic velocities and increased attenuation, but there is considerable disagreement about the depth of this structure and its effectiveness in trapping waves (e.g. Li et al., 2004 vs. Peng et al., 2003). Results of this work are significant as it is uncommon to have such an extensive, multi-
year data set from one borehole in addition to whole-rock core samples that can be compared to direct measurements of rock properties. Additionally, limited data exists on the \textit{in situ} elastic modulii of fault zones in the shallow crust.

The interdisciplinary nature of this research project provides insight into processes of weakening and localization of shear within active zones of SAF deformation in the SAFOD borehole. The accurate evaluation of rock properties in and around active fault zones is critical because they are key factors in controlling the dynamics of earthquake behavior.

References


Appendix A: Chapter 3 Tables
<table>
<thead>
<tr>
<th>Core Interval &amp; Core Run</th>
<th>Depth (m MD)</th>
<th>Lithologic Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Interval 1 Hole E Runs 1 Sections 1-4</td>
<td>3141.42 - 3144.6 (10306.5-10316.8)</td>
<td>Greemish Gray Pebby Arkosic Sandstone</td>
<td>Dark greenish-gray pebbly medium to coarse-upper arkosic sandstone occurs from the top of Hole E Core Run 1 Section 1 to the middle of Core Run 1 Section 4. It is comprised of three subunits distinguished on the basis of grain size. From 3142.4 to approximately 3141.9 m and from 3142.8 to 3144.6 m, the matrix is a coarse to very coarse, subangular to subrounded sand. Pebby clasts comprise 5 to 15 % of these subunits, and are subrounded to subangular, equant to slightly elongate (2:1 aspect ratio), dominantly feldspathic, and up to 2.5 cm in diameter. These clasts are mostly matrix supported in a grey-green silty sand matrix. The intervening subunit, from 3141.9 to 3142.8 m, has a similar matrix but distinctly fewer and smaller (granule size) clasts. Overall unit is massive and fines upwards and displays a slight interlocking grain texture. Coarse lenses contain subangular quartz, feldspar, and mica grains, with distinct irregularly shaped, dark reddish-brown volcanic-lithics and rare flakes of serpentinite. Thin-section analyses suggest a weak fabric of slight interlocking grain texture within the matrix suggestive of deformation and/or weak metamorphism.</td>
</tr>
<tr>
<td>Core Interval 1 Hole E Run 1 Sections 4-5</td>
<td>3144.6-3145.8 (10316.8-10,320.9)</td>
<td>Silty Shale and underlying Siltstone</td>
<td>A dark grayish-black siltstone extends from the middle of Core Run 1 Section 4 to nearly the bottom of Core Run 1 Section 5. Approximately 90% of this unit is comprised of mesoscopically homogeneous silt and clay size particles; the remainder consists of several subunits composed of fine to medium sands with pebbles less than 0.5 cm in diameter. One of the coarser subunits, located in the center of Section 5, is greenish-black in color and approximately 10 cm thick. The other subunit is a light olive-gray siltstone that shows faint pressure solution solutions and shearing near contact with the underlying grayish-red pebbly sandstone. Clasts in the coarser subunits are subrounded and predominately feldspathic in composition. A few thin (up to mm thick), non-quartz silicate veins (granite) are present. Subunit contacts are either gradational or are associated with distinct shear zones. The siltstone spanning the bottom of Section 4 and top of Section 5 is fractured and displays a weak scaly fabric.</td>
</tr>
<tr>
<td>Core Interval 1 Hole E Run 1 Sections 6-8, Run 2 Sections 1-6</td>
<td>3145.8-3152.6 (10,320.9-10,343.2)</td>
<td>Grayish-Red Pebby Sandstone</td>
<td>A grayish-red to brownish-gray pebbly sandstone exists between the fault contact located near the base of Core Run 1 Section 5 and the bottom of Core 2 Section 6. The matrix is composed of coarse- to very coarse subrounded sand. Clasts are up to 3 cm in diameter, subrounded to angular, elongate with aspects ratios up to 3 to 1, and dominantly feldspathic in composition. Bedding is defined by grain size variations, alignment of elongated clasts and Liesegang-type iron-oxide staining, and is subparallel (within 20 to 30 degrees) to the core axis. Several generations of fractures and mesoscale faults crosscut this unit. The mesoscale faults consist of layers of cataclasite that are up to 0.5 cm thick. Most of the fractures and faults are reddish- to dusky-brown, presumably from the oxidation of iron, zeolite veins that often are oriented at high angles to the foliation.</td>
</tr>
<tr>
<td>GAP IN CORE</td>
<td>Depth (m MD)</td>
<td>Lithologic Unit</td>
<td>Description</td>
</tr>
<tr>
<td>Core Interval 2 Hole G Core Run 1 Sec 1-6 to Core Run 2 Sec 1-3</td>
<td>3186.7-3193.9 (10455.2-10478.8)</td>
<td>Foliated Siltstone-Shale with Block-in-Matrix Fabric</td>
<td>The foliated siltstone-shale cataclasite extends from the top of Hole G Core Run 1 Section 1 to the middle of Core Run 2 Section 4. The cataclastic foliation is defined by a scaly fabric in the finer-grained portions, cm-thick color banding and shape fabrics formed by elongate, irregular-shaped lenses and porphyroclasts of siltstone and fine- to very fine-grained sandstone, and serpentinite. Clasts set within this fine matrix are commonly elongated, forming irregular stringers or pinch-and-swell structures with thin cross-cutting veins trending at high angles to the long axes of the clast. These lenses and porphyroclasts contain fine-grained calcite cement and pyrite(?), with numerous thin, short carbonate and zeolite veins that often are oriented at high angles to the foliation.</td>
</tr>
<tr>
<td>Core Run 2 Hole G Sec 4-5</td>
<td>3193.9-3196.4 (10478.8-10486.8)</td>
<td>Black Fault-related rock</td>
<td>Black fine- to ultra-fine grained massive and dense sheared fault-related rock extends from the middle of Core Run 2 Section 4 to the top of Core Run 2 Section 7. Bounding slip surfaces with extensive calcite veining parallel to the foliation direction occur at 3193.9 and 3195.8 m. Unit is</td>
</tr>
</tbody>
</table>

Table A-1. Lithologic and structural descriptions for SAFOD Phase 3 Core.
| Core Run 2 | Foliated Fault Gouge (SDZ) | Foliated gouge from the 3192 m zone of casing deformation is associated with the Southwest Deforming Zone (SDZ) after Zoback et al. (2010) and appears near the top of Core Run 2 Section 7 and continues to the bottom of the Run 2 core catcher. The gouge is a dark grayish-black, intensely sheared fault-related rock that is composed of particles that, for the most part, are <10 µm in diameter (defined using a 10X hand lens). The matrix is noncohesive and displays a wavy foliation defined by pervasive microscale shear zones that create a penetrative, micro-scaly fabric. Split surfaces are reflective and some are striated. |
| Hole G | 3196.4-3198 | ~ 3.9% of the total core |
| Sections 6-9 | |
| Core Run 3 | Interlayered Siltstone & Mudstone/Shale with Block-in-Matrix Fabric | A sheared siltstone and mudstone comprised of a thinly-bedded, dark, grayish-black shale, a grayish-black to olive-gray siltstone and very fine-grained sandstone. Bedding is approximately normal to the core axis, and is highly disrupted by offset along discrete mesoscale faults and by distributed shear of the shale. Coarser grained layers and lenses are well-cemented and cut by numerous shears and thin calcite veins that are oriented at high angles to the layering. Cataclastic shale is present at the top and base of the section. A drilling-induced highly fractured zone occurs in the middle of the section. |
| Hole G | 3198.4-3199.5 | ~ 2.7 % of the total core |
| Section 1 | |
| Core Run 4 | Siltstone | A sheared siltstone and sandstone characterized by greenish-black and dark greenish-gray, thinly bedded siltstone and very fine- to medium-grained sandstone that are disrupted by offset along discrete mesoscale faults and by more distributed shearing in the finer-grained layers. The more deformed bands of sandstone and sheared siltstone are dusky-brown, producing an obvious variegation. An approximately 15-cm-thick layer of greenish-gray sandstone occurs at the base of this unit; it displays a progressive loss of grain-scale cohesion with proximity to the contact with the foliated gouge below. |
| Section 1 to the bottom of Core Run 4 | 3294.9-3296.6 | ~ 4 % of the total core |
| Section 2 to the bottom of Core Run 4 Section 5 | Foliated Fault Gouge (CDZ) | The foliated gouge associated with the 3302 m zone of casing deformation or the Central Deforming Zone (CDZ) after Zoback et al. (2010), is similar in nature to the foliated gouge near the 3192 m fault, extends from the bottom of Core Run 4 Section 2 to the bottom of Core Run 4 Section 5. The gouge is a dark grayish-black, intensely sheared fault-related rock that is composed of particles that, for the most part, are <10 µm in diameter (defined using a 10X hand lens). The matrix is noncohesive and displays a wavy foliation defined by pervasive microscale shear zones that create a penetrative, micro-scaly fabric. Split surfaces are reflective and some are striated. Visible clasts ranging up to several cm in diameter make up about 5% or less of the volume. Porphyroclast lithology includes serpentine, very fine-grained sandstone and siltstone. Millimeter-size fragments of white (calcite?) veins also are present. Foliations are approximately |
| 3296.6-3299.1 | ~ 6.2% of the total core |
| Core Run 4 Section 5 to the top of Core Run 5 Section 2 | 3299.1-3301.5 (10,823.9-10831.7) | Sheared Siltstone/ Mudstone with Block-in-Matrix Fabric ~ 5.9 % of the total core | A highly sheared, dark gray to black finely laminated calcareous siltstone and mudstone unit extends from the bottom of Core Run 4 Section 5 to the top of Core Run 5 Section 2. Much of the unit is highly sheared but contains lenses or clasts of less deformed horizons. The sheared, somewhat foliated fabric plus any disrupted lithologic layering and some thin discontinuous veins are oriented at a moderately high angle to the core axis. Commonly the intrablock/clast veining does not extend into the surrounding matrix. |
| Core Run 5 Section 2 to the top of Core Run 5 Section 4 | 3301.5-3303.3 (10831.7-10837.6) | Interlayered Siltstone to Very Fine-grained Silty Sandstone with Block-in-Matrix Fabric ~ 4.4 % of the total core | Greenish-black to gray brown siltstone and very fine-grained massive sandstone extends from the top of Core Run 5 Section 2 to the top of Core Run 5 Section 4. The top portion of this unit contains several sharp, very dark shear surfaces with a dominant foliation inclined at ~75° to the core axis. The lower portion of this unit is mostly undeformed, very fine-grained siltstone with several distinct fractures. Locally, a meshlike network of indurated dark grey faults dip both up and down the core axis. |
| Core Run 5 Section 4 to the bottom of Core Run 5 Section 7 | 3303.3-3305.9 (10837.6-10846.2) | Sheared and Fractured Siltstone to Very Fine Sandstone with Block-in-Matrix Fabric ~ 6.4 % of the total core | Medium dark-gray to light-gray siltstone to very fine sandstone extends from the top of Core Run 5 Section 4 to the bottom of Core Run 5 Section 6 (and possibly into Section 7, which has not yet been examined in detail). This unit fines downward and is dominated by deformation features consisting of 2 to 8 cm thick gouge/shear (clay-rich?) zones, all at ~ 40° to the core axis, and numerous parallel to subparallel alternating zones of cataclasite, breccia and/or noncohesive rubble. These deformed zones are interspersed with less sheared siltstone. Within this sequence are 1 to 4 cm long subrounded clasts of finely laminated siltstone to fine sandstone of similar composition to overlying units. Some boundaries of these clasts are sheared, and a few clasts contain 1 to 2 mm wide calcite veins. Pyrite is present locally within this unit. A more deformed zone starts at about 3304.8 m and extends to the bottom of this unit. This deformed zone consists of very fine-grained dark greenish gray/black siltstone and mudstone with numerous sheared surfaces and a breccia zone containing mm-sized fragments and polished striated surfaces. |
| Core Run 6 Section 1 to the top of Core Run 6 Section 5 | 3307.4-3311 (10851.0-10862.9) | Sheared and Fractured Claystone, Mudstone and Siltstone with Block-in-Matrix Fabric ~ 7.8 % of the total core | A dark gray black calcareous mudstone/claystone extends from the top of Core Run 6 Section 1 to the top of Core Run 6 Section 5. This unit contains a mixture of rubble zones (caused by drilling) of sheared material exhibiting a scaly fabric, and numerous subangular matrix blocks within these sheared zones. Much of the unit consists of fractured and deformed rocks with the larger clasts appearing less-deformed relative to the overlying units. Striated surfaces are still common on smaller fragments within the sheared zones. The brecciated dark-gray siltstone/mudstone and sheared siltstone is cut by several “microbreccia” zones. The dominant shear fabric is at high angles to the core axis. Especially in the upper sections, the core is quite friable and slightly soft to the touch where it is moist and contains some clay. This unit appears to coarsen into predominately siltstone and becomes slightly more indurated toward its base, where there is a transition zone containing interspersed sheared zones in a dark-gray to greenish-black finely laminated siltstone and dark gray mudstone. |
| Core Run 6 Section 5 to bottom of Core Run 6 Section 6 | 3311-3312.7 (10862.9-10868.5) | Sheared Claystone and mudstone gouge ~ 4.2 % of the total core | Sheared, grayish black claystones and mudstones within a brecciated and foliated sheared siltstone extend from the top of Core Run 6 Section 5 to the bottom of Section 6. Two large indurated clasts with prominent calcite veining are near the top of this unit. Two fold hinges of the folded foliation are present in the central part of the unit. |
Table A2. Microscale observations and whole-rock powder X-ray diffraction (XRD) results from select Phase 3 whole-rock core and powdered samples. XRD compositions are listed in order of the relative estimation of different phase proportions. The identification of phases is based on analyses of the bulk XRD patterns using X´Pert High Score software as part of the X´ Pert Pro XRD system. For phases in the shales and/or fine-grained gouges not visible at the thin-section scale, verification is required by further analyses. Within these phyllosilicate-rich materials many of the peaks may overlap, thus, mineral identifications can be challenging for phases present in only small quantities. We also used optical microscopy of cuttings (Bradbury et al., 2007) for correlation. In terms of reporting these minor to trace phases, we chose a minimum threshold score match of ~15. A) Samples analyzed by author at Utah State University; B) For comparative reference, samples prepared and analyzed at similar depth intervals at the U.S.G.S. Menlo Park Office by D.E. Moore (Phase 3 Core Photo Atlas v. 3-4 at http://www.earthscope.org/observatories/safod) are included.

<table>
<thead>
<tr>
<th>Sample Location</th>
<th>Geologic Featured Sampled</th>
<th>Meso- to Micro-scale Observations</th>
<th>XRD Mineralogical Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>3142 m* [10308.4 ft] ER1S1</td>
<td>Lithic Arkosic Sandstone</td>
<td>Subangular quartz and feldspar grains show intra/inter granular fracturing; concentration and weak alignment of phyllosilicate grains within matrix; etched quartz grain boundaries and overgrowth structures, diffusion of grain boundaries, grain boundary migration; alteration of biotite to chlorite; fibrous clay matrix with crystallization and/or replacement by calcite and clay minerals</td>
<td>Quartz + Plagioclase (Albite &amp; Anorthite) + Microcline + Muscovite Mica + titanium aluminosilicate ± Ankerite ± Palygorskite ± Illite ± Zeolite</td>
</tr>
<tr>
<td>3144 m [10315 ft] ER1S3</td>
<td>Lithic Arkosic Sandstone</td>
<td>Extensive intra/inter-granular microfracturing; cataclastic bands are present; slightly recrystallized; deformation lamellae and pressure solution seams occur in coarser quartz fragments; grains are subangular to subrounded; irregular mafic volcanic lithics (basalt?) suggest glass has converted to clay</td>
<td>Quartz + Plagioclase (Albite + Anorthoclase) + Microcline ± Ankerite ± Lizardite ± Sepiolite ± Cr-oxide</td>
</tr>
<tr>
<td>3144.6 m * [10317 ft] ER1S4</td>
<td>Sheared Silty Black Shale/ Mudstone</td>
<td>Texturally immature with abundant angular grains, increased magnetite concentration, green mineral (serpentine &amp;/or palygorskite)</td>
<td>Quartz ± Plagioclase (Albite) ± Magnetite ± Lizardite ± Palygorskite ± Illite</td>
</tr>
<tr>
<td>3146.3 m* [10322.65 ft] ER1S6</td>
<td>Feldspathic Arkosic Sandstone</td>
<td>Extensive fracturing and grain comminution/cataclasis; concentration of oxides/hydroxides along slip surfaces; calcite exhibiting deformation twinning is present in veins; pressure solution seams occur in coarse quartz fragments; all grains pervasively fractured</td>
<td>Quartz ± Albite ± Microcline</td>
</tr>
<tr>
<td>3147.5 m [10326.4 ft] ER1S7</td>
<td>Feldspathic Arkose</td>
<td>Extensive cataclasis, microfracturing, and microfaults with multiple offsets ~ 1-3 mm.</td>
<td>Quartz</td>
</tr>
</tbody>
</table>

A)
<table>
<thead>
<tr>
<th>Depth</th>
<th>Description</th>
<th>Mineralogy</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>3147.5 m</td>
<td>Fracture Surface Coating</td>
<td>Cataclasite and clay with felt mineral growth along fracture surfaces</td>
<td>Quartz ± Albite ± Orthoclase ± Smectite (Nontronite?) ± Palygorskite</td>
</tr>
<tr>
<td>3150.3 m</td>
<td>Feldspathic Arkosic Sandstone</td>
<td>Extensive cataclasis, microfracturing, and microfaults with multiple offsets ~ 1-3 mm.</td>
<td>Quartz ± Albite ± Mica ± Smectite (Nontronite)</td>
</tr>
<tr>
<td>3150.3 m*</td>
<td>[10335.6 ft] ER2S2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3187.4 m</td>
<td>Clast</td>
<td>Clast entrained within fine-grained phyllosilicate-rich gouge; clast contains fine to very-fine grained zones of microbreccia offset by carbonate and/or zeolite veins; opaque lined microfractures link to zones of injected cataclasite comprised of opaque fine-grained ground mass containing porphyroclasts of quartz and claystone</td>
<td>Quartz + Magnetite ± Albite ± Kaolinite ± Palygorskite ± Zeolite (Gismondine) ± Garnet (Ti-rich Andradite)</td>
</tr>
<tr>
<td>3187.5 m*</td>
<td>[10457.6 ft] GR1S2</td>
<td>Foliated Phyllosilicate-rich Matrix</td>
<td>Quartz + Kaolinite ± Magnetite + Albite ± Palygorskite ± Calcite ± Garnet (Ti-rich Andradite)</td>
</tr>
<tr>
<td>3189 m</td>
<td>Finely laminated Siltstone and Shale Clast and/or Layer</td>
<td>Cataclasite with opaque groundmass surrounds altered and reworked cataclasite fragments containing intraclast veins; numerous anastomosing to stylolitic opaque fractures bound multiple layers/generations of cataclasite</td>
<td>Quartz + Magnetite + Albite ± Palygorskite ± Calcite ± Garnet (Ti-rich Andradite)</td>
</tr>
<tr>
<td>3190.1 m*</td>
<td>[10466.2 ft] GR1S3</td>
<td>Finely laminated Siltstone and Shale Clast and/or Layer</td>
<td>Smectite (Nontronite) ± Magnetite + Albite ± Kaolinite ± Palygorskite</td>
</tr>
<tr>
<td>3191.5 m</td>
<td>Foliated Phyllosilicate-rich Matrix</td>
<td>Opaque pressure solution seams form weak fabric within clast; localized injection of fine-grained opaque ground mass/cataclasite.</td>
<td>Quartz + Calcite + Kaolinite + Albite ± Garnet (Ti-rich Andradite ± Almandine) ± Palygorskite ± Carbon</td>
</tr>
<tr>
<td>3192.7 m*</td>
<td>Black Cataclasite to Ultracataclasite</td>
<td>Ultrafine sheared black matrix rock with quartz porphyroclasts and larger lens-shaped clasts of cataclasite with crack-seal (?) calcite veins</td>
<td>Quartz + Carbon + Magnetite + Palygorskite ± Mica ± Illite ± Lizardite ± Cr-oxide -hydroxides ± Ni-oxide -hydroxides ± Garnet (Almandine)</td>
</tr>
<tr>
<td>3192.7 m</td>
<td>Fracture Surface Coating</td>
<td>Ultrafine multilayered sheared matrix with quartz porphyroclasts</td>
<td>Quartz + Mica + Carbon (Graphite?) ± Chrysotile ± Magnetite ± Palygorskite</td>
</tr>
<tr>
<td>3193 m</td>
<td>Black Cataclasite to Ultracataclasite</td>
<td>Ultrafine dark altered groundmass surrounding altered rounded to subrounded grains of similar composition; quartz porphyroclasts and isolated amygdalae of unknown composition are visible</td>
<td>Quartz + Magnetite ± Mica ± Garnet (Almandine) ± Palygorskite</td>
</tr>
<tr>
<td>3193.9 m*</td>
<td>Foliated Cataclasite</td>
<td>Ultrafine alternating black to dark brown to light brown (ppl) foliated to brecciated groundmass cross cut by numerous vein cycles</td>
<td>Quartz + Magnetite + Albite ± Chlorite-Serpentine ± Sepiolite ± Nontronite ± Fe-Ni-oxides</td>
</tr>
<tr>
<td>3193.9 m*</td>
<td>[10478.7 ft] GR2S4</td>
<td></td>
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<tr>
<td>Depth (m)</td>
<td>Color</td>
<td>Type of Rock</td>
<td>Description</td>
</tr>
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<td>-------</td>
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<td>-------------</td>
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<tr>
<td>3194.8 m</td>
<td>Black</td>
<td>Cataclasite to Ultracataclasite</td>
<td>Similar to 3193.9 m</td>
</tr>
<tr>
<td>3195.8 m</td>
<td>Black</td>
<td>Cataclasite to Ultracataclasite</td>
<td>Ultrafine cataclasite, less foliated than similar rocks above; extensive irregular fracture geometries surrounding clasts of microbreccia and reworked foliated cataclasite</td>
</tr>
<tr>
<td>3196.28 m</td>
<td>Black</td>
<td>Cataclasite to Ultracataclasite</td>
<td>No thin section available</td>
</tr>
<tr>
<td>3197.7 m*</td>
<td>Black</td>
<td>Fine-Grained foliated matrix with sandstone, serpentinite, and garnet porphyroclasts; several porphyroclasts are mantled with opaque oxides or clays forming eye-shaped to bow-tie flow patterns suggestive of high-strain; anastomosing foliated gouge exhibits well-developed S-C fabric</td>
<td>Quartz + Opal-A + Sepiolite ± Allevardite ± Zeolite (Stilbite) ± Nickel-oxide-hydroxide</td>
</tr>
<tr>
<td>3197.9 m</td>
<td>Foliated Fault Gouge (SDZ)</td>
<td>Similar to 3197.72 m above with a greater variety of porphyroclast compositions</td>
<td>Quartz + Montmorillonite + Albite + Nontronite + Nickel-oxide-hydroxide + Serpentine (Lizardite) ± Zeolite (Dickite) ± Magnetite</td>
</tr>
<tr>
<td>3197.9 m</td>
<td>Serpentinite Clast (SDZ)</td>
<td>Phacoidal shaped green clast entrained within foliated phyllosilicate-rich gouge matrix</td>
<td>Quartz + Calcite ± Plagioclase (Albite + Anorthoclase) ± Serpentine (Chrysotile) ± Zeolite (Dickite) ± Magnetite</td>
</tr>
<tr>
<td>3295 m</td>
<td>Banded Siltstone</td>
<td>Subangular to angular grains within silt-rich layers; detrital serpentinite grains; quartz-rich matrix; abundant aragonite</td>
<td>Quartz ± Plagioclase (Albite) + Magnetite ± Illite ± Phillipsite</td>
</tr>
<tr>
<td>3295 m</td>
<td>Fracture Surface Coating</td>
<td>Subangular to angular silty layers alternating with sheared clayey matrix; calcite and aragonite in veins</td>
<td>Quartz + Magnetite + Titanite ± Illite ± Smectite (Nontronite) ± Cristobolite</td>
</tr>
<tr>
<td>3295.8 m*</td>
<td>Sheared Siltstone and Shale</td>
<td>Shear localization in clay-rich zones with altered fibrous minerals parallel to open extensional fractures; calcite microveins crosscut fine laminations</td>
<td>Quartz ± Plagioclase (Albite) ± Serpentine (Chrysotile) ± Illite ± Smectite (Nontronite) ± Magnetite</td>
</tr>
<tr>
<td>3297.4 m</td>
<td>Foliated Fault Gouge (CDZ)</td>
<td>Anastomosing scaly clay fabric surrounding rounded to subrounded clasts of reworked cataclasite and serpentinite with pods or zone of darker stained groundmass</td>
<td>Saponite + Serpentine (Clinochrysotile) + Quartz + Plagioclase (Anorthite) ± Carbon ± Al-Hydroxide (Gibbsite?)</td>
</tr>
<tr>
<td>3298.4 m*</td>
<td>Foliated Fault Gouge (CDZ)</td>
<td>Similar to SDZ samples described above</td>
<td>Saponite + Quartz + Serpentine (Clinochrysotile Lizardite) ± Dashkovite? (salt)</td>
</tr>
<tr>
<td>3299.06 m</td>
<td>Sheared Siltstone and Serpentinite Clasts</td>
<td>Angular to subangular siltstone cut by discrete zones of cataclasite and carbonate and/or magnesite (?) veins; Serpentinite clast appears massive and highly altered containing opaque oxides and cut by opaque hairline fractures</td>
<td>Calcite + Quartz + Opal-A + Nontronite + Albite + Serpentine (Antigorite + Lizardite) ± Magnesite ± Cr-oxide-hydroxide</td>
</tr>
<tr>
<td>Sample Location</td>
<td>Geologic Feature Sampled</td>
<td>XRD Mineralogical Composition</td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
<td>--------------------------</td>
<td>--------------------------------</td>
<td></td>
</tr>
</tbody>
</table>
| 3190.6 m  
[10468 ft]  
GR1S5 | Foliated Siltstone-Shale Cataclasite | Quartz + Plagioclase (Albite) ± mixed layer clays (I/S?) ± Calcite (?) ± Chlorite |
| 3192.3 m  
[10473.5 ft]  
GR2S2 | Foliated Siltstone-Shale Cataclasite | Quartz + Plagioclase (Albite) + Illite (phengite) + Calcite + Chlorite ± mixed layer clays (I/S?) |
| 3196.5 m  
[10487.1 ft]  
GR2S7 | Foliated Fault Gouge (SDZ) | Quartz + Plagioclase (Albite) + Calcite ± Serpentine ± Chlorite-Smectite (Corrensite?) |
| 3196.9 m  
[10488.8 ft]  
GR2S7 | Sheared Serpentine-bearing Fault Gouge (SDZ) | Serpentine (Lizardite ± Chrysotile) + Quartz + Calcite + Chlorite-Smectite (Corrensite?) |
| 3197.2 m  
[10489.4 ft]  
GR2S7 | Foliated Fault Gouge (SDZ) | Quartz + Plagioclase (Albite) + Calcite ± Illite (phengite?) ± Chlorite-Smectite (Corrensite?) |

*Indicates corresponding X-ray florescence sample listed in Table2- 3.

**B)**
Table A-3. Whole-rock geochemistry of selected SAFOD Phase 3 samples: (A) Unnormalized Major Elements (Weight %); B) Unnormalized Trace Elements (ppm).

### A) Major Elements

<table>
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<tr>
<th>Sample Depth</th>
<th>SiO2</th>
<th>Al2O3</th>
<th>FeO*</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na2O</th>
<th>K2O</th>
<th>TiO2</th>
<th>P2O5</th>
<th>Total Al</th>
<th>Si, Mg, Fe, Ca, Na, K, Ti, P</th>
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</thead>
<tbody>
<tr>
<td>3197.7 m [10491.3 ft] GR2S8</td>
<td>69.64</td>
<td>1.06</td>
<td>0.149</td>
<td>0.342</td>
<td>0.65</td>
<td>0.616</td>
<td>0.57</td>
<td>0.50</td>
<td>0.493</td>
<td>0.198</td>
<td>0.718</td>
<td>0.341</td>
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<tr>
<td>3196.7 m [10515.9] GR4S3</td>
<td>62.22</td>
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<td>1.05</td>
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<td>3.30</td>
<td>2.77</td>
<td>7.64</td>
<td>7.14</td>
<td>14.28</td>
<td>6.95</td>
<td>8.01</td>
</tr>
<tr>
<td>3297.1 m [10817.2] GR4S3</td>
<td>7.00</td>
<td>5.33</td>
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<td>0.916</td>
<td>0.02</td>
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<td>0.02</td>
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<td>0.068</td>
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<tr>
<td>3301.3 m [10831.2] GR5S2</td>
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<td>1.57</td>
<td>1.59</td>
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<tr>
<td>3308.7 m [10855.7] GR6S2</td>
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<td>1.75</td>
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<td>0.68</td>
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<td>4.01</td>
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<td>3.03</td>
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<td>0.75</td>
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<tr>
<td>3312.0 m [10864.6] GR6S6</td>
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<td>4.63</td>
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<td>4.17</td>
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### B) Trace Elements

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<th>Sample Depth</th>
<th>Cr</th>
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<th>Ni</th>
<th>Cu</th>
<th>Zn</th>
<th>As</th>
<th>Se</th>
<th>Mo</th>
<th>Hg</th>
<th>Sb</th>
<th>Bi</th>
<th>Total</th>
<th>Sn, Pb, Zn, Cu, Co, Ni, Cr, As</th>
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</thead>
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<td>0.18</td>
<td>0.27</td>
<td>0.18</td>
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<td>0.27</td>
<td>0.18</td>
<td>0.30</td>
<td>0.30</td>
<td>0.68</td>
<td></td>
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<tr>
<td>3197.7 m [10491.3 ft]</td>
<td>1.70</td>
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<td>0.28</td>
<td>0.20</td>
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<td>0.18</td>
<td>0.30</td>
<td>0.30</td>
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<tr>
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**Table Data:**
- Column headers: Rb, Sr, Zr, Y, Nb, Ga, Cu, Zn, Pb, La, Ce, Th, Nd, U.
- Rows represent different elements.

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Appendix B: Chapter 4 Tables
Table B1: Summary Deformation and Alteration in SAFOD fault-related rocks. Refer to Appendix B2-B4 included in the Supplemental CD for additional sample information for each unit.

<table>
<thead>
<tr>
<th>CORE SAMPLE DEPTH RANGE</th>
<th>LITHOLOGIC / STRUCTURAL UNIT</th>
<th>DEFORMATION STYLE</th>
<th>MESO-SCALE TEXTURE</th>
<th>MICRO-SCALE TEXTURE</th>
<th>SEM TEXTURE</th>
<th>ALTERATION</th>
<th>TOC%</th>
</tr>
</thead>
<tbody>
<tr>
<td>3187.4 – 3192.7</td>
<td>Foliated siltstone/shale with block-in-matrix fabric</td>
<td>Brittle and Distributed [Transition Zone – Moderate to Low Strain Zone]</td>
<td>Block-in-Matrix with Pinch-and-Swell Structure Veins Restricted to Clasts Clasts Moderately to Intensely Deformed Pervasive Scaly Clay Matrix</td>
<td>Breciated Clasts with Carbonate and Silica Micro-Veins Cataclasite Injected Cataclasite Oxides Aligned in Fractures</td>
<td>Conglobulated Clay Platy Clay Coated Discrete Slip Surfaces</td>
<td>Si High Carbonates Fe, Ti-oxides (Magnetite) Fe-sulfides CIA: Moderate To High LOI: Low</td>
<td>0.9 - 1.5</td>
</tr>
<tr>
<td>3192.7 - 3196.3</td>
<td>Black Fault-related rock</td>
<td>Brittle [Transition to Fault Core – High Strain Zone]</td>
<td>Aphanitic, Ultra-fine Cataclasite; Veins Cross-Cut Matrix and Parallel to Foliation Surfaces Injection of Black Carbonaceous Material</td>
<td>Layered Cataclasite Clay Transformation Discrete Slip Surfaces Carbonate Micro-Veins Oxides Aligned in Fractures</td>
<td>Compacted Cataclasite Platy Clay Coated Discrete Slip Surfaces Open to healed microfractures Carbonaceous Matter</td>
<td>Si Moderate Calcite veins Fe-oxides Fe-sulfides CIA: Moderate LOI:</td>
<td>0.4-1.1</td>
</tr>
<tr>
<td>3299.1 – 3301.5</td>
<td>Foliated siltstone/shale</td>
<td>Brittle and Distributed</td>
<td>Block-in-Matrix with Anastomosing Fabric near</td>
<td>n/a</td>
<td>Si Low MG-oxides</td>
<td>0.7-1.9</td>
<td></td>
</tr>
</tbody>
</table>
Note, due to the nature and size of the remainder of Appendix C Data and Tables are included in a Supplemental CD:

- **Table B2-A**: Petrographic and Geochemical Samples Examined: Samples collected from SAFOD Phase 3 Core.

- **Table B2-B**: Petrographic and Geochemical Samples Examined: Samples Collected from San Simeon (SS) and Goat Rock (GR) Field Localities in Central to Northern California.

- **Table B3-A**: Major and Trace Element Whole-Rock Geochemical Data based on XRF analyses for SAFOD Core.

- **Table B3-B**: Total Organic Carbon (TOC) analyses results for selected SAFOD core samples.

- **Table B4**: Dmod Values (Medley and Goodman, 1994) Measured for clasts present in SAFOD Phase 3 Core, excluding the SDZ and CDZ shear zones.
Appendix C: Chapter 5 Data Tables
Density and resistivity data from the core are measured directly on the core in the laboratory with depths representing depth within the core sidetrack and not the main SAFOD borehole. All other data files are measured via downhole logging tools directly in the main SAFOD borehole. Velocity data was matched from the main borehole files compiled by Jeppson et al. (2010) using moving averages over a 2m interval. Each 2 meter interval average is calculated in step-format to create unique point depths for a 0.5 m interval with the average value given at 0.25 and 0.75. Note, the depths are not at the same exact interval, therefore, matching of the data is located to the nearest .01 – to .001 ft interval.

Table C1. Lithologic descriptions and geophysical properties of Phase 3 Core for each unit. Fault-related rocks discussed in Chapter 4 are highlighted.

<table>
<thead>
<tr>
<th>Core Interval &amp; Depth (m MD)</th>
<th>Depth (m MD) (ft MD)</th>
<th>Lithologic Unit</th>
<th>Geophysical Properties Averaged over core depth (No Depth Correction)</th>
<th>Geophysical Properties Averaged over core depth (Depth Correction after Zoback et al. 2010)</th>
</tr>
</thead>
</table>
| Core Interval 1 Hole E Runs 1 Sections 1-4 | 3141.42 – 3144.6 (10306.5 - 10316.8) | Greenish Gray Pebby Arkosic Sandstone 7.5 % of total core sampled | $V_p$: 5.37 km/s  
$V_s$: 3.09 km/s  
$\rho$: 2.59  
$\mu$: 23.87  
$\lambda$: 31.82  
E: 61.27  
v: 0.28 | n/a* |
| Core Interval 1 Hole E Run 1 Sections 4-5 | 3144.6-3145.8 (10316.8-10,320.9) | Silty Shale and underlying Siltstone 3.2 % of total core sampled | $V_p$: 5.39 km/s  
$V_s$: 3.04 km/s  
$\rho$: 2.65  
$\mu$: 20.98  
$\lambda$: 33.44  
E: 54.78  
v: 0.30 | n/a* |
| Core Interval 1 Hole E Run 1 Sections 6-8, Run 2 Sections 1-6 | 3145.8-3152.6 (10,320.9-10,343.2) | Grayish-Red Pebby Sandstone ~ 16.6 % of total core sampled | $V_p$: 5.00 km/s  
$V_s$: 2.98 km/s  
$\rho$: 2.59  
$\mu$: 24.28  
$\lambda$: 30.64  
E: 61.87  
v: 0.28 | n/a* |
| GAP IN CORE | | | | |
| Core Interval 2 Hole G Core Run 1 Sec 1-6 to Core Run 2 Sec 1-3 | 3186.7-3193.9 (10455.2-10478.8) | Foliated Siltstone-Shale with Block-in-Matrix Fabric ~ 17.5 % of the total core | $V_p$: 4.79 km/s  
$V_s$: 2.85 km/s  
$\rho$: 2.57  
$\mu$: 21.26  
$\lambda$: 17.47  
E: 51.68  
v: 0.22 | $V_p$: 4.89 km/s  
$V_s$: 2.78 km/s  
$\rho$: 2.57  
$\mu$: 19.84  
$\lambda$: 22.33  
E: 50.13  
v: 0.26 |
| Core Run 2 Hole G Sec 4-5 | 3193.9-3196.4 (10478.8 - 10486.8) | Black Fault-related rock ~ 8.5 % of the total core | $V_p$: 3.69  
$V_s$: 2.17  
$\rho$: 2.59 | $V_p$: 4.79  
$V_s$: 2.81  
$\rho$: 2.57 |
<table>
<thead>
<tr>
<th>Core Run</th>
<th>Section</th>
<th>Range</th>
<th>Description</th>
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<tr>
<td>Run 4 Section 2</td>
<td>3299.1-3301.5</td>
<td>(10,823.9-10,831.7)</td>
<td>Sheared Siltstone/Mudstone Block-in-Matrix melange textures</td>
</tr>
<tr>
<td>Run 5 Section 2</td>
<td>3298.4-3199.5</td>
<td>(10,493.5-10,497.2)</td>
<td>Interlayered Siltstone &amp; Mudstone/Shale with Block-in-Matrix Fabric</td>
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<tr>
<td>Run 4 Section 2</td>
<td>3296.6-3299.1</td>
<td>(10,815.5-10,823.9)</td>
<td>Foliated Fault Gouge (CDZ) ~ 6.2% of the total core</td>
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<tr>
<td>Core Interval 3</td>
<td>Hole G</td>
<td>3294.9-3296.6</td>
<td>Siltstone ~ 4% of the total core</td>
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<td>Core Run 4</td>
<td>Hole G</td>
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<td>(108.100-10815.5)</td>
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<td>Core Run 4</td>
<td>Sections 6-9</td>
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<td>3294.9</td>
<td>(108.100-10815.5)</td>
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<td>3296.6</td>
<td>(10,815.5-10,823.9)</td>
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<td>(10,823.9-10,831.7)</td>
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<td>(10,823.9-10,831.7)</td>
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<tr>
<td>Core Run 5</td>
<td>Section 2 to the top of Core Run 5 Section 4</td>
<td>3301.5-3303.3</td>
<td>(10831.7-10837.6)</td>
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<tr>
<td>Core Run 5</td>
<td>Section 2 to the top of Core Run 5 Section 4</td>
<td>3301.5-3303.3</td>
<td>(10831.7-10837.6)</td>
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</table>
| Core Run 6 Section 1 to the top of Core Run 6 Section 5 | 3307.4 -3311 (10851.0-10862.9) | Sheared and Fractured Claystone, Mudstone and Siltstone with Block-in-Matrix Fabric | v: 0.27 | \( V_p: 3.56 \)  
\( V_s: 1.93 \)  
\( V_p/V_s: 1.84 \)  
\( \rho: 2.54-2.57 \)  
\( \mu: 9.01 \)  
\( \lambda: 12.55 \)  
E: 12.20  
v: 0.28 | \( V_p: 3.21 \)  
\( V_s: 1.86 \)  
\( V_p/V_s: 1.72 \)  
\( \rho: 2.47 \)  
\( \mu: 8.44 \)  
\( \lambda: 8.22 \)  
E: 20.90  
v: 0.23 |
| Core Run 6 Section 5 to bottom of Core Run 6 Section 6 | 3311-3312.7 (10862.9-10868.5) | Sheared Claystone and mudstone gouge | v: 0.29 | \( V_p: 3.43 \)  
\( V_s: 1.90 \)  
\( V_p/V_s: 1.80 \)  
\( \rho: 2.54-2.57 \)  
\( \mu: 9.09 \)  
\( \lambda: 12.27 \)  
E: 23.39  
v: 0.28 | \( V_p: 3.29 \)  
\( V_s: 1.85 \)  
\( V_p/V_s: 1.77 \)  
\( \rho: 2.36 \)  
\( \mu: 8.72 \)  
\( \lambda: 11.49 \)  
E: 22.38  
v: 0.28 |

*Depth corrections not completed for Hole E. Data averaged from

Note, due to the nature and size of the remainder of Appendix C Data and Tables are included in a Supplemental CD:

- Table C2: Calculated Averages of Elastic Moduli for SAFOD Phase 2 and Phase 3 Cored Intervals.
- Table C3: Borehole Geophysical Logging Data and Calculated Rock Properties for SAFOD Borehole from 3013 to 3990 m MD.
- Table C4: Calculated 100 m averages of Elastic Moduli for the SAFOD Borehole from 3031 to 3931 m MD.
- Table C5: Velocity, Density, and Resistivity Parameters from SAFOD Borehole Geophysical Logging Data.
- Table C6: Foreloop script created in MATLAB with assistance from Anthony Lowry. The script was used to generate the depth ranges for each Cluster data set as shown in Figure 5-5.
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Please indicate your approval of this request by signing the letter where indicated below and returning a copy of this letter to the Geology Department either via Fax at 435-797-1588, scanned and sent through email, or mailed directly to the department address listed below.

Thank You,

Kelly Keighley Bradbury, Graduate Student
Geology Department, Utah State University
4305 Old Main Hill
Utah State University
Logan, UT 84322-4505
kellykbradbury@gmail.com

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By: [signature]

Title: Frederick Chester

Date: 5 April 2012
April 4, 2012

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I am in the process of preparing my written dissertation as part of completion of my Doctoral degree at Utah State University and I am seeking permission to include the Earth and Planetary Science Research Letter’s paper you were listed on as a coauthor for one of my chapters.

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Logan, UT 84322-4505
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PERMISSION GRANTED FOR THE USE REQUESTED ABOVE:

By: Judith S. Chester

Title: Professor of Geology, Texas A&M University

Date: 4/20/2012
April 4, 2012

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By: Daniel Corey Barton
Title: Geologist, Anadarko Petroleum Corporation
Date: 4/4/2012
April 4, 2012

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By: [Signature]
Title: Associate Professor
Date: 4/19/2012
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By: Sarah Springer
Title: [Blank]
Date: 04-05-2012
April 4, 2012

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CERTIFICATION
Licensed Professional Geologist, State of Utah

EDUCATION
Ph.D. Candidate, Utah State University, Logan UT (August 2007 - present)
Dissertation Title: Geological, Geochemical, and Geophysical properties of Fault-related rocks at SAFOD (San Andreas Fault Observatory at Depth): Implications for Fault-related Processes, San Andreas Fault, California.
Advisor: Dr. James P. Evans

M.S. Geology: Utah State University, Logan, UT (1999)
Thesis Title: Structural and Hydrogeological Analyses of Deformed Sedimentary Bedrock Aquifers in the Pinebrook Subdivision, Western Summit County, UT
Advisor: Dr. James P. Evans

B.S. Major: Geology, Minor: Mathematics, Western Michigan University, Kalamazoo, MI (1993)
Undergraduate Thesis Title: Mapping Buried Bedrock Aquifers Using Geophysical Techniques, Lake Michigan Shoreline, Benton Harbor, MI
Advisor: Dr. Estella Atekwana

RESEARCH SUMMARY
Investigate composition, internal structure, and alteration products of natural fault zones
Utilize integrated approach including structural geology, geologic mapping, drillhole based studies, petrology, whole-rock geochemistry, stable isotopic studies, hydrogeology, and geophysics
Strong background in meso-to micro-scale geologic observations and fracture analyses
Extensive laboratory experience in microscopy (petrographic, SEM), X-ray diffraction techniques, grain-size analyses, particle-size distributions, specific gravity measurements
Experience spans a diverse range of rock types across a variety of geologic and tectonic settings
Communicate results to colleagues and scientific community effectively through active participation in presentations at national meetings and peer reviewed publications
WORK EXPERIENCE
Exploration Manager/Senior Geologist, Paris Hills Agricom, Bloomington, ID (April 2011–present)
Conduct detailed geologic surface mapping, cross-section development, drillcore logging and characterization, fracture analyses, and regional exploration activities

Research Assistant, Utah State University, Logan, UT (Jan 2008 – present)
Examine composition and internal structure of the San Andreas fault in SAFOD borehole, California.

Teaching Assistant, Utah State University, Logan, UT (Aug 2007 – Dec 2007)
Mineralogy Lab Assistant
Coordinate study-group times and lead mineral identification sessions

Field Camp Teaching Assistant, Field Camp, Utah State University, Logan, UT (June 2008)
Assist instructor in helping students for geologic mapping project in Great Basin National Park, Nevada

X-Ray Lab Technician, Utah State University, Logan, UT (June 2007-May 2011)
Manage USU X-Ray Diffraction Laboratory; facilitate and schedule instrument maintenance
Process samples for faculty, staff, students, and public or industry requests
Serve in leadership role to train graduate and undergraduate students in sample preparation, laboratory techniques, spectra analyses and assist with their research projects

Geologic Consultant, Smithfield, UT (July 2001 – Jan 2007)
Investigated fault zone properties within various rock types using fine-scale geologic mapping, petrographic and whole-rock geochemical analyses, and sedimentological techniques to quantify hydrologic properties of fault-related structures

Principal Geoscientist, UF³, North, Logan, UT (June 2002 – Aug 2007)
Characterized fracture permeability and porosity controls related to deformation within oil-bearing reservoirs, CA and UT
Collaborate with other scientists and work as part of a team to develop integrated resource assessment of fractured reservoirs
Coordinated and conducted field reviews, collected data, and produced graphics for fracture characterization field courses offered through International Nautilus Geoscience Training Alliance
Identified critical deformation and fluid flow elements related to deformation in sedimentary rocks for 3D fracture model constraints
Fault seal analysis of small offset normal fault in siliciclastic sequences within Utah and Idaho for SATOIL, Norway
Created detailed subsurface geologic cross-section profiles based on well log data for Bear River Water Conservancy District, UT
Environmental Scientist, Cirrus Ecological Solutions, Logan, UT (Aug 1999- Dec 2000)
Evaluated geologic hazards (seismic, slope stability, avalanche) for EIS of Snowbird Ski Resort, UT
Surveyed well locations and well characteristics for proposed Ruby Gas Pipeline, UT-WY

Consulting Hydrogeologist, BIO/WEST Inc., Logan, UT (Jan - Mar 2000)
Delineated Drinking Water Source Protection zones based on ground water modeling and compiling pre-existing hydrogeologic data and maps, UT

Geology Technician, Energy and Geoscience Institute, Salt Lake City, UT (Aug 1997-Dec 1998)
Compared results of fracture data measured on core to borehole televiwer image logs from the Valles Caldera, NM
Mapped and interpreted fracture data from deformed limestone outcrops for analog studies
Digitized geophysical well logs and developed numerous illustrations for presentations and publications

Field Technician, Watershed Science Dept., Utah State University, Logan, UT (Aug 1996)
Collected stream channel dimensions and mapped riparian vegetation using GIS for the assessment of riparian degradation and endangered fish habitats due to historic mining activities in Leadville, CO

Research Assistant, Utah State University, Logan, UT (Aug 1994 – May 1997)
Mapped geologic structures and conducted detailed fracture surveys within heterogeneous, multiply deformed, compartmentalized sedimentary aquifers near Park City, UT
Field assistant for project involving detailed geologic mapping of small strike-slip fault zones in granitic outcrops within the John Muir Wilderness region, Sierra Nevada, CA
Developed conceptual model of fracture intensities and proposed potential test well sites, Park City, UT

Teaching Assistant, Utah State University, Logan, UT (Aug 1994 – May 1996)
Physical Geology and Structural Geology classes

Field Technician, Western Michigan Univ., Kalamazoo, MI (Jun 1992 – Oct 1993)
Collected geophysical data using gravity, magnetics, electrical and Ground Penetrating Radar
Delineated depth and 2D geometry of buried stream channel aquifers for water resource evaluation
Processed data using mathematical equations and 2-D modeling software
AWARDS AND HONORS
- USU Robins Awards Finalist, PhD Student Researcher of the Year (2010)
- USU College of Science PhD Student Researcher of the Year (2010)
- Peter R. McKillop Memorial Scholarship Recipient, Department of Geology (2008, 2009)
- Utah State University Dept. of Geology Graduate Student Researcher of the Year (1997)
- Western Michigan University Top Senior in Geology Award (1992)

FUNDING AWARDED
- GDL Foundation Research Grant $1500 (2009)
- Society for Petrophysicists and Well Log Analysts Research Grant $7800 (2008/2009)
- Society for Exploration Geophysicists Academic Scholarship $12,000 (2008/2009)
- Drilling, Observation, and Sampling Earths Continental Crust (DOSECC) Internship $5000 (2008)
- USU Women’s Center Re-entry Student Award $1500 (2008-2009)
- Colorado Scientific Society Research Grant $ 500 (1996)
- Geological Society of America Student Research Grant $1500 (1995)
- Utah State University Dept. of Geology J.S. Williams Scholarship $600 (1996)
- National Association of Geology Teachers Field Course Scholarship $300 (1993)
- Western Michigan University Honors-Student Research Grant $1000 (1992-1993)

PUBLICATIONS


Bradbury, K.K., Barton, D.C., Solum, J.G., Draper, S.D., and Evans, J.P, 2007, Mineralogical and textural analyses of drill cuttings from the San Andreas Fault Observatory at Depth (SAFOD) boreholes: Initial interpretations of fault zone composition and constraints on geologic models, *Geosphere*, v. 3;


PRESENTATIONS AND ABSTRACTS


Bradbury, K.K., and J.P. Evans, 2010, Composition and structure of SAFOD Phase III Whole Rock Core: Implications for fault zone deformation and fluid-rock interactions, Geol. Soc. of America Abstracts with Programs, v. 42, no. 5, p. 476.


Evans, J.P., Jeppson, T.N., Bradbury, K.K., and A.R. Lowry, Evaluation of fault zone structure and properties at depth, with insights into deformation and alteration of the San Andreas fault at SAFOD, Eos Trans. AGU, 90(53), Fall Mtg. Suppl., Abstract
Bradbury, K.K., and Evans, J.P., 2009, Franciscan Formation within the SAFOD Borehole, near Parkfield, CA, Geol. Soc. of America Abstracts with Programs V. 41, No. 7., p. 404.


PROFESSIONAL FIELD TRIPS AND REPORTS

PROFESSIONAL AFFILIATIONS
American Geophysical Union
Geological Society of America
Society for Petrophysicists and Well Log Analysts

*REFERENCES (upon request)