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Franciscan Complex geology northeast of Calaveras Reservoir, Diablo Range, California

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**FRANCISCAN COMPLEX GEOLOGY NORTHEAST OF CALAVERAS
RESERVOIR, DIABLO RANGE,
CALIFORNIA**

A Thesis

Presented to

The Faculty of the Department of Geology

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Ron S. Rubin

December 2002

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APPROVED FOR THE DEPARTMENT OF GEOLOGY

A handwritten signature in black ink, appearing to read 'R. Sedlock', written over a horizontal line.

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Dr. John Wakabayashi, Independent Consultant

APPROVED FOR THE UNIVERSITY

A handwritten signature in black ink, appearing to read 'J. [unclear]', written over a horizontal line.

ABSTRACT

FRANCISCAN COMPLEX GEOLOGY NORTHEAST OF CALAVERAS RESERVOIR, DIABLO RANGE, CALIFORNIA

by Ron S. Rubin

Field mapping and thin section analysis provide the first detailed lithologic, petrologic, and structural data on Franciscan Complex rocks near Calaveras Reservoir. Coherent tracts of sandstone, similar to the Yolla Bolly terrane, and *mélange* comprise most of the study area. These units are juxtaposed along low-angle, bedding-parallel faults, and were deformed mainly by pressure solution. Detrital blueschist minerals in the sandstones imply Franciscan exhumation much earlier than previously documented. Detrital modes of coherent, *mélange* matrix, and *mélange* block sandstones suggest a common protolith, and a *mélange* matrix distinct from those studied elsewhere. A fault-bounded block in the northwestern part of the study area contains distinctive Franciscan rocks such as interbedded chert and sandstone, and a horse of Temblor Sandstone indicating a previously unmapped late Cenozoic fault zone. Franciscan map units and structures in the study area are not contiguous to the north, and a Mesozoic fault may separate the areas.

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geology, and this thesis has greatly benefited from my association with Bob in my time at SJSU.

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Plate

1. Geologic Map and Structure Sections from the Area East of Calaveras
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INTRODUCTION

Many classic papers about subduction zone processes, structures, and metamorphism have been based on work done on the Franciscan Complex of California (e.g., Coleman and Lee, 1963; Bailey et al., 1964; Hsu, 1968; Ernst, 1970). Based on these and other works, many subsequent studies of the Franciscan have expanded the current understanding of subduction complexes (e.g., Cowan, 1974; Page, 1981; Cloos, 1982; Blake et al., 1984; Platt, 1986; Wakabayashi, 1992). An important element in many of these studies is field mapping. However, many parts of the Franciscan Complex have not been mapped in detail due to problems with poor outcrop quality and private property conflicts. In addition, most of the existing maps of the Franciscan Complex are of pre-plate-tectonics age, and thus lack an understanding of the significance of certain rock types and structures that are commonly the focus of subduction zone research today.

The main objective of this study is to produce a detailed geologic map of the Franciscan Complex in an area that, to date, has only been studied in reconnaissance. In addition, petrology, structure, and aspects of geologic history of the Franciscan rocks in the study area are reported on for the first time. These types of data are essential to understanding the geology of an area, and for evaluating possible future research goals in the area. Thus, this study will provide valuable information not only to those who are trying to integrate geologic information on the northern Diablo Range, but also to those searching for areas with potential for additional detailed research.

Location and Access

The study area is located within the northwestern corner of the Diablo Range along the northeast margin of Calaveras Reservoir, bordering Alameda and Santa Clara counties, California. Calaveras Reservoir is about 18 km (11 mi) northeast of San Jose, and about 64 km (40 mi) southeast of San Francisco, on Calaveras Road. Gated access roads to the reservoir property are located at the north and south ends of the reservoir, off Calaveras Road and Marsh Road, respectively (Fig. 1). Access to the Calaveras Reservoir property must be formally granted by the property owner, the Water Department of the San Francisco Public Utilities Commission.

The San Francisco Water Department maintains an extensive network of unpaved roads on the Calaveras Reservoir property. These roads, which include the main Oak Ridge Road, extend far beyond the study area and also have gated intersections with various other private properties. The major roads are mapped on USGS 7.5' quadrangles, but other roads maintained less frequently are not shown on those maps.

Road access to areas adjacent Alameda Creek can also be obtained through the Sunol Regional Wilderness on Geary Road. Sunol Regional Wilderness is a public park leased to the East Bay Regional Parks District. A gated, maintained, unpaved road extends from the end of Geary Road through the park.

Study Area Conditions

The Diablo Range is a north-northwest-trending mountain range that extends northward from around Cholame to its northern termination in the Livermore Valley.

Figure 1. Location map of the Calaveras Reservoir study area.

The Diablo Range is a sub-province of the California Coast Ranges province and forms the eastern boundary between the Coast Ranges and the Great Valley of central California. The study area occupies an area near the northwest termination of Oak Ridge, which is part of a series of northwest-trending ridges that comprise the northern end of the Diablo Range.

Oak Ridge Road follows the most prominent ridgeline in the study area (Plate 1, grid areas 3-B, 3-C, and 4-C). The southeast corner of section 18 contains a prominent plateau at an elevation of about 1700 feet (518 m). The highest peak in the map area is just over 2500 feet (762 m), and the nominal water level on the reservoir and Arroyo Hondo tributary is about 765 feet (233 m), but varies seasonally. Alameda Creek is at an elevation of about 900 feet (274 m) at the east end of the field area near the diversion dam, and at about 550 feet (168 m) at the west end of the field area near Calaveras Creek. The steepest slopes are locally about 1:1 and are essentially inaccessible. Loose soil, colluvium, and heavy vegetation in steep areas also inhibit accessibility.

Calaveras Reservoir is man-made, but the basin it fills may be associated with active late Cenozoic faulting. Active faulting has created many distinct geomorphic depressions within the Diablo Range such as Halls Valley, Anderson Reservoir, and Coyote Reservoir (Schwartz et al., 2002). Faulting, bedrock type, and structure also contribute locally to expression of geomorphic features such as landslides, gullies, and streams.

Vegetation in the study area is primarily controlled by sun exposure. North-facing slopes contain abundant large trees, grasses, and shrubs, and south-facing slopes

are primarily grassy and spotted with trees that are typically concentrated in gullies. As a result of the abundant soil and vegetation, the area of individual bedrock outcrops comprise <1% of the total surface area, and most outcrops are <5 m². Road grading has created some of the most extensive outcrops on the property.

Study Area Boundaries

The study area occupies the northernmost portion of the Calaveras Reservoir 7.5' quadrangle, and the southernmost portion of the La Costa Valley 7.5' quadrangle. The north and south map area boundaries are Alameda Creek and Arroyo Hondo, respectively. The eastern map area boundary was determined by access permission complications, and the western map area boundary was determined primarily based on previous mapping performed by others.

Previous Work

To date, the only published maps that cover the Franciscan Complex at Calaveras Reservoir have been reconnaissance (Crittenden, 1951; Cotton, 1972; Crawford, 1975; Dibblee, 1973; Dibblee, 1980; Graymer, et al., 1996; Wentworth et al., 1999). Ernst (1971a) performed a petrologic study of Franciscan sandstones in the northern Diablo Range that included areas around Calaveras Reservoir. Nilsen et al. (1975) and Helley et al. (1994) mapped surficial deposits in the area. Graymer et al. (1996) and Wentworth et al. (1999) mapped the area adjacent to the reservoir in greater detail than the rest of their study area due to the proximity of the Calaveras fault (Russell Graymer, personal

communication, 2000). Therefore, my study did not duplicate their mapping in that area. A master's thesis by Christie (1985) in Sunol Regional Park, adjacent to the study area to the north, included a detailed investigation of the Franciscan Complex.

Mapping Techniques

The geologic map produced as part of this study was mapped in the field at a scale of 1:12,000. Locations of contacts between geologic units were determined based on contrasts in lithology, texture, and structure; due to variable outcrop quality, many contacts were estimated on the basis of changes in topography. For example, a resistant sandstone unit is more likely to hold up a steep slope than a *mélange* unit with recessive shale matrix. At best, contacts are obscured by covered intervals that are 2-3 m wide. Samples were collected from map units (Plate 1) and during reconnaissance outside of the study area. Blocks smaller than about 35 m are not shown to scale on the geologic map, and for the most part, the locations of individual blocks in areas of landsliding were not mapped.

SUMMARY OF FRANCISCAN COMPLEX GEOLOGY

The Franciscan Complex is a component of a late Mesozoic-Tertiary arc-trench system consisting of the Franciscan subduction complex, the Great Valley forearc basin, and the Sierra Nevada arc (Dickinson, 1970a). Franciscan Complex rocks were subducted, deformed, and metamorphosed, most to blueschist-facies, beneath the leading edge of North America (e.g., Hamilton, 1969; Ernst, 1970). The Franciscan Complex is structurally overlain by the Late Jurassic Coast Range ophiolite. The Great Valley Group, which depositionally overlies the ophiolite, is a section mainly of deepwater turbidites that filled the forearc basin between the trench and magmatic arc. The ophiolite and Great Valley Group have undergone low-grade burial metamorphism.

Pre-Franciscan tectonic history involved a complex series of plate interactions involving multiple arcs, subduction zones, probable transform segments, and episodes of oceanic crust generation. These interactions are recorded in pre-Franciscan rocks exposed in the Sierra Nevada and Klamath Mountains. Many workers do not agree on even the broad details of this tectonic history, but the following studies and references therein represent some of the current ideas: Moores (1970), Schweickert and Cowan (1975), Shervais (1990), and Dickinson et al. (1996).

The ideas discussed herein provide a framework in which to interpret some of my own studies. For more comprehensive reviews, see Bailey et al. (1964), Page (1981), Blake et al. (1984), Cloos (1986), and Wakabayashi (1992).

Rock Types

The Franciscan Complex contains a wide range of rock types of various origins. All have been metamorphosed and recrystallized to some degree, but many primary features are preserved. In generally decreasing abundance, they include clastic sedimentary rocks, basaltic volcanic rocks (i.e., greenstone), chert, limestone (e.g., Sliter, 1984; Sliter et al., 1986), and rarer intrusive rocks (e.g., Bailey et al. 1964). Serpentinite is also a minor part of the Franciscan (e.g. Blake et al., 1984; Coleman, 2000), although much of the serpentinite associated with the Franciscan is actually part of the Coast Range ophiolite.

Marine Sedimentary Rocks

Most of the Franciscan Complex is comprised of massive to well-bedded sandstone that contains local interbeds of mudstone and shale, channelized conglomerates, and rare but widespread chert interbeds. Interbedded chert and sandstone occurrences are well-known in the Franciscan Complex (e.g., Raymond, 1974; Page, 1981; Worrall, 1981; Blake et al., 1984). However, the drastic difference in rate of deposition between the two rock types precludes a simple explanation of depositional processes and environments. Murchey and Jones (1984) and Karl (1984) address possible depositional environments. In contrast, Isozaki and Blake (1994) identified sequences of clastic sediments and chert that are in contact along closely-spaced imbricate faults.

Petrologic studies show that most Franciscan sandstones are arkosic (e.g., Jacobson, 1978; Dickinson et al., 1982; Jayko and Blake, 1984). Franciscan clastic sediments probably were deposited in submarine fan settings within the forearc and trench, and on the abyssal plain (e.g., Blake and Jones, 1974; Telleen, 1977; Jacobson, 1978; Dickinson et al., 1982). The rarely exposed contact of sandstones that overlie greenstone and chert probably represents the basal contact of continentally derived strata atop underlying oceanic crust (e.g., Isozaki and Blake, 1994; Blake and Wentworth, 1999).

Chert is also widespread within the Franciscan Complex. Chert typically forms well-bedded sections with variably preserved radiolarians and thin shale interbeds. A relatively complete section at Marin Headlands records about 100 m.y. of pelagic deposition at equatorial latitudes (Murchey and Jones, 1984; Hagstrum and Murchey, 1993). Geochemical and sedimentologic evidence suggests that cherts at Marin Headlands originated as pelagic deposits at equatorial latitudes and changed up-section, reflecting progressively more continental influence Karl (1984).

Fossils in the Franciscan Complex are widespread and have well-established paleontologic ages, but they are sporadically distributed so there is poor control on depositional age of large parts of the Franciscan (Fig. 2). Most of the fossils are from pelagic sedimentary rocks that were probably deposited long before they were subducted. Fossils in Franciscan clastic rocks are very rare. Thus, paleontologic ages do not constrain subduction processes very well.

Figure 2. Compilation of some Franciscan Complex fossil and metamorphic ages. High-grade blocks are distributed throughout Franciscan mélanges, and the other units are generally distributed from east to west from the top of the page downward. Abbreviations: AFT—apatite fission track; Ar—Ar-⁴⁰Ar/³⁹Ar step heating, except wrtf—whole-rock total fusion; fch—fossils from chert; fls—fossils from limestone; fss—fossils from clastic rocks; K/Ar—potassium-argon; U/Pb—U/Pb isochron method, ZFT—zircon fission track. Mineral abbreviations: act—actinolite, biot—biotite, hbl—hornblende, WM—white mica, wr—whole rock. Sources: Lee et al. (1964), Coleman and Lanphere (1971), Suppe and Armstrong (1972), Lanphere et al. (1978), Suppe and Foland (1978), Mattinson and Echeverria (1980), McDowell et al. (1984), Mattinson (1986), Ross and Sharp (1988), Dumitru (1989), Wakabayashi and Deino (1989), Tagami and Dumitru (1996), Weinrich (1997). Older K/Ar dates recalculated using decay constants of Steiger and Jager (1977). Adapted from Wakabayashi (1999a).

Igneous Rocks

Greenstone, or metabasalt, is often closely associated with the marine sedimentary rocks. Where greenstone underlies sections of chert and/or sandstone, it is interpreted as the oceanic crust on which the sediments were deposited (Murchey and Jones, 1984; Hagstrum and Murchey, 1993). The greenstone locally shows pillow structures, suggesting eruption on the sea floor, possibly at a spreading ridge. Blake et al. (1984) present geochemical data indicating that an extensive greenstone terrane (Nicasio Reservoir) originated as ocean-island tholeiites and ocean-ridge basalts.

A few gabbroic dikes and sills have been documented within various parts of the Franciscan (Echeverria, 1980; Worrall, 1981; Jayko et al., 1986; Isozaki and Blake, 1994). Most of these bodies intrude sedimentary rocks, reflecting the relative timing of intrusion, subduction, and metamorphism (e.g., Mattinson and Echeverria, 1980). Based on geochemical data, Isozaki and Blake (1994) suggested an off-ridge setting of intrusion.

Terranes

In an attempt to organize and improve understanding of Franciscan Complex structure and history, geologists have divided fault-bounded groups of rocks within the Franciscan into individual tectonostratigraphic terranes based on characteristic age, structure, and lithology. Terranes provide a convenient way of describing and comparing various parts of the Franciscan. Due to Cenozoic deformation associated with the transform plate boundary, the various terranes and subdivisions do not always reflect

original subduction complex structure or tectonostratigraphy (e.g., Page, 1981; Wakabayashi, 1992).

The concept of “belts” within the Franciscan Complex was first developed in northern California, where the Franciscan was divided into three northwest-trending belts. Berkland et al. (1972) formalized the terms Coastal belt (Bailey and Irwin, 1959) and Eastern belt (Blake, 1965) by defining the belts’ boundaries relative to the their newly defined Central belt (Fig. 3). In the San Francisco Bay region, these belts are more difficult to recognize due to both Cenozoic deformation and the internal structural complexity of the Franciscan (Wakabayashi, 1992).

Blake et al. (1982, 1984) were the first to subdivide the Franciscan Complex in the San Francisco Bay region into tectonostratigraphic terranes (Fig. 4). The terrane nomenclature was also extended to northern California, further subdividing some of the belts described above (Fig. 3).

Metamorphism

Metamorphism within the Franciscan Complex has played an important role in understanding the geologic history of subduction complexes (e.g., Ernst, 1970, 1971b; Ernst et al., 1970). Although the Franciscan contains a wide variety of metamorphic grades, it is best-known for blueschist-facies metamorphism (e.g., Ernst, 1970). Most of the blueschist-facies rocks in the Franciscan are coherent metasedimentary rocks with primary textures so well-preserved that large parts of the Franciscan were unidentified as

Figure 3. Distribution of the Franciscan Complex in central and northern California. Map also shows distribution of adjacent Great Valley Group and Coast Range Ophiolite rocks. The three major terranes of Franciscan rocks are differentiated. Coastal and Central terranes are re-named from their respective belts, and the original Eastern belt has been divided into the Yolla Bolly and Pickett Peak terranes. Approximate location of study area at X. Modified from Moore and Blake (1989).

Figure 4A. Tectonostratigraphic terrane map of the San Francisco Bay area, northern half. Modified from Blake et al. (1984).

Figure 4B. Tectonostratigraphic terrane map of the San Francisco Bay area, southern half. Approximate location of study area shown by X. Modified from Blake et al. (1984).

metamorphic rocks until petrographic inspection in the late 1950s (McKee, 1962, cited in Cloos, 1986). In fact, most of the Franciscan is neither blue nor schistose.

Most rocks in the Franciscan Complex are metamorphosed to blueschist facies, and some of the older high-grade blocks are eclogites and amphibolites that have a blueschist overprint (Moore and Blake, 1989; Wakabayashi, 1990). The blueschist-facies index minerals lawsonite, jadeite, glaucophane, and aragonite are found in varying abundance in Franciscan coherent terranes, *mélange* blocks, and *mélange* matrix.

Blueschist-facies mineral assemblages commonly found in the Franciscan Complex form at pressures of about 5-8 kb, corresponding to depths of 15-30 km, and temperatures of about 100-300°C (Ernst, 1965, 1971b, 1993). The initial metamorphic conditions for high-grade glaucophane schist and eclogite blocks are estimated at 450-800°C, and 9-12 kb (Wakabayashi, 1987, 1990; Moore and Blake, 1989; Krogh et al., 1994). Shale *mélange* matrix was metamorphosed at pressures of 3-10 kb but temperatures of only 100-250°C (Cloos, 1983).

Cloos (1986) and Ernst (1993) discuss the distribution of blueschist-facies rocks in the Franciscan Complex as a whole. They note that blueschist occurrences are widespread and abundant, but there is no systematic pattern in either the distribution of high-grade *mélange* blocks, or in the abundance of high-pressure assemblages within coherent terranes. Transitions from one assemblage or textural zone to the next are commonly abrupt, and probably marked by faults, some of which may be bedding-parallel and difficult to recognize in coherent sandstone and shale sections. However, the

Franciscan does show a regional east-to-west (or structurally high to low) decrease in metamorphic grade (e.g., Blake et al., 1988)

There are many well-established radiometric ages from metamorphic minerals within Franciscan Complex rocks (Fig. 2). High-grade *mélange* blocks generally are the oldest components of the Franciscan. Ages from coherent terranes span considerable time both internally, and across the spectrum of ages for all coherent terranes. Because different techniques have different precision, accuracy, and mineralogic constraints, some radiometric dates cannot be directly compared with each other (Wakabayashi, 1992). Nevertheless, several trends are apparent from the age data that bear on process-oriented aspects of Franciscan evolution. For example, while the high-grade blocks were being metamorphosed at depth, oceanic sedimentary rocks were being deposited. The latter then were subducted and metamorphosed while younger rocks were being deposited. This suggests that subduction, metamorphism, and deposition were coeval, at least at certain times throughout the history of Franciscan subduction (Worrall, 1981; Wakabayashi, 1992). Another common tendency is for depositional/eruptive ages of protoliths to differ significantly from the metamorphic, or docking ages that record the rocks' incorporation into the accretionary wedge (e.g., Wakabayashi, 1992; Murchey and Blake, 1993).

Mélange

The Franciscan Complex contains extensive *mélange* terranes (e.g., Cloos, 1986), which were mapped as stratiform sequences by early workers (e.g., Lawson, 1914;

Taliaferro, 1943; Crittenden, 1951). To address the origin of the Franciscan and its relation to the coeval Great Valley Group, Hsu (1968) formally applied the *mélange* concept to the Franciscan. Hsu suggested the fault-bounded blocks be called “tectonostratigraphic units,” a strategy that Blake et al. (1982) would comprehensively apply to the Franciscan as a whole.

Hsu proposed that *mélanges* originate from tectonic mixing of rocks that may be stratigraphically or structurally unrelated, and he distinguished *mélanges* from olistostromes, which are chaotic units deposited by marine sedimentary processes (Hsu, 1968). Others have proposed that at least some Franciscan *mélanges* originated as olistostromes (e.g., Crawford, 1975; Cowan, 1978; Aalto, 1982; Aalto and Murphy, 1984; Moore, 1984; Erickson, 1995). This interpretation is often difficult to test because pervasive deformation obscures many primary sedimentary features within the matrix, and important contacts with adjacent coherent units are often unexposed (Page, 1981). Most Franciscan *mélanges* are generally considered to be of tectonic origin (e.g., Cowan, 1974; Cloos, 1982; Blake et al., 1988), although sedimentary disruption may have contributed in some *mélanges* (Hsu, 1968; Gucwa, 1975). Cloos (1982), Cowan (1985), and Wakabayashi (1992) summarize various models for the origin of *mélanges*.

The largest tract of Franciscan *mélange*, known as the Central terrane (Blake et al., 1984), can be traced almost continuously from the San Francisco Bay Area to northernmost California, and in places is up to 40 km across (Fig. 4). There are also many other smaller *mélange* tracts, some of which occur within coherent (i.e., non-*mélange*) terranes (e.g., Cowan, 1974; Crawford, 1975; Blake and Wentworth, 1999). In the

Diablo Range, for example, coherent terranes are separated by the Garzas *mélange*, but the *mélange* also is locally interleaved with the coherent units (Blake and Wentworth, 1999). *Mélange* blocks range in size from a few centimeters to many kilometers across. *Mélange* matrix is mostly shale, but also locally contains sandstone interbeds (e.g., Jacobson, 1978; Worrall, 1981; Jayko and Blake, 1984).

Franciscan Complex *mélanges* contain blocks that are lithologically similar to, and likely derived from, coherent terranes of the Franciscan. Many workers have also noted the similarity of some blocks to immediately adjacent coherent terranes (e.g., Cowan, 1974; Worrall, 1981). *Mélanges* also contain rare exotic blocks of high-grade blueschist, amphibolite, and eclogite that are the most well-known and intensely studied aspect of Franciscan geology. The origins of these exotic blocks are still speculative because there are no known source terranes (e.g., Worrall, 1981). High-grade blocks may have a pre-Franciscan origin (e.g., Coleman and Lanphere, 1971; Blake et al., 1988), or may have originated during the earliest stages of Franciscan subduction (e.g., Platt, 1986; Wakabayashi, 1990). The latter model may be supported by the observation that the high-grade blocks seem to be concentrated at the structurally highest and oldest parts of the Franciscan, and by the presumption that the geothermal gradient was higher during initiation of subduction (e.g., Worrall, 1981; Platt, 1986; Wakabayashi, 1992).

Cloos (1982) developed a dynamic model to explain not only the possible origin of high-grade blocks, but also the origin and development of Franciscan *mélanges* in general. His model accounts for the effects of thermal conditions, as well as the mechanics responsible for *mélange* development and dispersal of high-grade blocks. In

short, this model proposes convection within the accretionary wedge at the interface between the hanging wall and downgoing plate. Convection provides a mechanism for uplifting and mixing the high-grade blocks, and his P-T model accounts for the blueschist overprint of amphibolite and eclogite blocks (Cloos, 1985).

Ages of individual *mélange* terranes are not well-constrained because of sporadic fossil occurrences and unexposed or faulted contacts with adjacent units. *Mélanges* occur in Franciscan terranes of all ages, and contain blocks with ages that generally span the entire age of the Franciscan (e.g., Page, 1981; McLaughlin et al., 1982; Blake et al. 1988). Though structurally lower *mélanges* contain old, high-grade blocks, they also contain some of the youngest blocks found in *mélange* (e.g., Maxwell, 1974; Wakabayashi, 1992). Thus, ages of the youngest blocks and relative ages of the faulting at least constrain the maximum age of *mélange* development and juxtaposition with coherent terranes.

Franciscan Structure

Franciscan Complex structural geology is heterogeneous due to the accretionary processes by which it was formed. This can be accounted for by along-strike variation in materials being accreted (e.g., Wakabayashi, 1992, 1999a,b), or by syn-subduction strike-slip faulting (e.g., Blake and Jones, 1981; McLaughlin et al., 1988; Murchey and Blake, 1993). Franciscan structure has been complicated further by subsequent late Cenozoic faulting associated with the San Andreas transform fault system (e.g., Page, 1981; Ernst, 1993; Wakabayashi, 1992, 1999a,b; McLaughlin et al., 1996). Structures related to

subduction zone deformation are often difficult to distinguish from those due to late Cenozoic shortening, which may produce the same types of thrusts that are commonly interpreted as Franciscan structures. Also, most of the Franciscan now lies beneath extensive soil and vegetative cover, which further obscures structural relationships.

The overall structure of the Franciscan Complex is generally visualized as a stack of imbricate thrust sheets that young downward in incorporation age (Blake et al., 1984; Jayko et al., 1986; Wakabayashi, 1992). Blake et al. (1984) and Wakabayashi (1992) envision the nappe stack folded into broad synforms and antiforms. This structure is consistent with a long-lived accretionary wedge (Wakabayashi, 1992), and is developed by underplating of progressively younger, coherent sedimentary units (e.g., Maxwell; 1974; Platt, 1986).

Faults in the Franciscan are commonly oriented subparallel to bedding and/or foliation, and many are post-metamorphic (e.g., Worrall, 1981; Blake and Jayko, 1983; Ernst, 1993; Blake and Wentworth, 1999). Faults that separate coherent units are generally considered to have a thrust sense of slip because, on a large scale, highly metamorphosed older terranes structurally overlie less recrystallized younger terranes. However, few kinematic indicators have been observed.

The Franciscan Complex in the northern California Coast Ranges clearly displays imbricate structure. Both age and degree of metamorphism generally decrease from east to west, i.e., structurally downward (Maxwell, 1974; Jayko et al., 1986; Blake et al., 1988). Cowan (1974), Page (1981), and Blake and Wentworth (1999) have shown that the Diablo Range of central California is an antiformal stack of two coherent Franciscan

terrane that are separated by *mélange*. The upper terrane (Yolla Bolly or Eylar Mountain) is more highly recrystallized than the younger and structurally lower terrane (Burnt Hills). Some faulting and folding, at least within the older terrane, is thought to have occurred prior to metamorphism (e.g., Mattinson and Echeverria, 1980). However, Blake and Wentworth (1999) suggest that juxtaposition of the terranes and incorporation of *mélange* occurred after metamorphism.

Coherent terranes typically are composed of sedimentary rocks, and have locally preserved remnants of basal igneous and rarer intrusive rocks. The coherent terranes are up to hundreds of kilometers long, and are generally surrounded by shale-matrix *mélange* along fault contacts (Blake et al., 1984). Most coherent terranes are less-deformed than the *mélange* matrix or high-grade *mélange* blocks, and though some have a high degree of textural reconstitution (e.g., Pickett Peak terrane) they retain relatively consistent internal lithology and structure. However, the progressions of metamorphic and textural grades within coherent terranes are abrupt and non-systematic, probably due to faults at low angles to bedding that have unknown displacements (e.g., Suppe and Foland, 1978; Jayko et al., 1986; Ernst, 1993).

Structures in the shale *mélange* matrix are difficult to interpret because of limited exposure and the high susceptibility of the matrix to surficial mass wasting. Where observed, the *mélange* matrix generally is pervasively sheared and has scaly cleavage (e.g., Cowan, 1974; Cloos, 1986). *Mélange* blocks of all lithologies typically have an ellipsoidal shape (Bailey et al., 1964; Cloos, 1982, 1986), and commonly show boudinage or pinch-and-swell structure. Cataclastic deformation along the margins of

blocks dies out toward the block interiors (e.g., Cowan, 1978; Cloos, 1986). The long axes of blocks commonly are oriented parallel to the foliation of the matrix, which wraps around the periphery of the blocks (Cloos, 1986). The significant shearing in the matrix shale indicates it has accommodated the bulk of the strain.

Exhumation of the Franciscan Complex

Exhumation of blueschist-facies rocks to their current structural level is one of the major problems in understanding accretionary processes. The occurrence of blueschist detritus in Franciscan sedimentary rocks has implications for understanding the timing and rate of blueschist exhumation, and subsequent subaerial exposure. Detrital grains of blueschist-facies minerals in the Franciscan Complex are widespread but rare (e.g., Cowan and Page, 1975; Moore and Liou, 1980). Brothers and Grapes (1989) proposed that, alternatively, many blueschist-facies minerals are detrital and all jadeite is detrital, based on textural and mineral chemistry evidence. Raymond (1991) contested this hypothesis, acknowledging that while there may be some occurrences of blueschist detritus, there is unmistakable evidence that these uncommon occurrences are the exception rather than the rule.

Five main processes have been proposed for the exhumation of blueschists in the Franciscan and elsewhere: 1) erosion of the upper portion of the accretionary wedge, 2) normal faulting or extension of the upper wedge during successive underplating and thickening of the lower wedge (Platt, 1986), 3) a combination of erosion and ductile thinning by pressure solution, which results in sub-vertical shortening (Feehan and

Brandon, 1999; Ring and Brandon, 1999), 4) ductile return flow (Cowan and Silling, 1978), analogous to Cloos' model of *mélange* formation, and 5) extrusion of large fault bounded blocks (e.g., Maruyama et al., 1996).

Regardless of how exhumation occurred, there are several constraints on the process. As mentioned above, blueschist assemblages are widely preserved without evidence for a high-temperature overprint. Fission-track data support at least one episode of syn-subduction exhumation (15 km of the Yolla Bolly terrane at 100-70 Ma) (Tagami and Dumitru, 1996), and is corroborated by geometry and timing of deformation in the Great Valley Group (Wakabayashi and Unruh, 1995). Blueschist detritus is rare in Franciscan and coeval Great Valley Group sedimentary rocks (Platt, 1986), but there must have been some exposures to account for the documented occurrences.

Post-subduction Franciscan Complex History

Franciscan subduction continued until mid-Tertiary time at Californian latitudes. By about 29 Ma encroachment of the Pacific-Farallon ridge with the Farallon-North American trench began to terminate subduction near the latitude of modern Los Angeles (Atwater, 1970). Deformation associated with activity on the current transform plate boundary has manifested itself chiefly as dextral strike-slip faults. Because the Pacific-North American relative motion is not parallel to these faults, local transtension and transpression have produced thrust faults, normal faults, mountain ranges, structural basins, and folds (e.g., Page, 1981; Page et al., 1998). Thrust faults may be confused with Franciscan faults where no younger rocks involved in the faulting.

LOCAL GEOLOGIC SETTING

The study area is located within the northern Diablo Range, California (Fig. 4). The Diablo Range is an antiformal stack with a core of Jurassic to Cretaceous blueschist-facies Franciscan Complex rocks, and a mantle of unmetamorphosed Upper Jurassic to Cretaceous forearc strata of the Great Valley Group (Fig. 3; Page, 1981; Ernst, 1993). These two units are juxtaposed along high-angle Cenozoic faults: the Calaveras fault in the west, and the Tesla-Ortogonalita fault in the east. The contact between the Franciscan Complex and the Great Valley Group is commonly marked by the presence of the Middle Jurassic Coast Range Ophiolite, which underlies the Great Valley Group.

Franciscan Complex rocks of the Diablo Range consist mainly of *mélange* and coherent slabs of marine sedimentary rocks. Coherent blueschist-facies clastic units include the Late Cretaceous Burnt Hills terrane (Blake, 1981), and the structurally higher, Late Jurassic to Early Cretaceous Yolla Bolly terrane (e.g., Fig. 4, Blake and Wentworth, 1999). The Yolla Bolly terrane of the Diablo Range was originally called the Eylar Mountain terrane (Blake, 1981), but has since been correlated with similar rocks originally named for exposures in northern California (Blake et al., 1982, 1984). *Mélange* separates and is interleaved with the coherent terranes along fault contacts (Blake and Wentworth, 1999). All *mélange* in the Diablo Range was named the Garzas *mélange* (Cowan, 1974) by Blake and Wentworth (1999). The *mélange* contains blocks and slabs of sandstone, greenstone, and radiolarian chert, as well as rarer blueschist,

eclogite, and amphibolite, in a matrix of sheared shale and minor sandstone (e.g., Blake and Wentworth, 1999; Wentworth et al., 1999).

Franciscan rocks near Calaveras Reservoir are part of the Yolla Bolly terrane, which consists mainly of coherent blueschist-facies sandstone, lesser mudstone and radiolarian chert, and *mélange*. Just west of the study area is the Calaveras fault, an active, high-angle, right-lateral fault of the San Andreas fault system. Based on detailed mapping of this study, and by Graymer et al. (1996), pre-Holocene strands of the Calaveras fault may exist in the western part of the study area.

ISSUES ADDRESSED IN THIS STUDY

Data from this study provides the opportunity for the evaluation of the following specific problems: 1) detrital blueschist in Franciscan sandstones and their implications for timing and rate of exhumation; 2) comparative detrital modes of Franciscan coherent sandstone, *mélange* matrix sandstone, and *mélange* block sandstone; 3) late Cenozoic faulting; 4) along-strike variations in Franciscan geology; 5) deformation mechanisms in Franciscan sandstones; and 6) Franciscan sandstone-chert contacts.

LITHOLOGIC DESCRIPTIONS

This section contains lithologic and petrologic descriptions of rocks of the Franciscan Complex, which underlies most of the study area. At the end of this section, I describe rocks of the early Miocene Temblor Sandstone that are in contact with the Franciscan rocks. Descriptions are based on field notes, descriptions of hand samples in the laboratory, and petrographic analyses. The common lack of quality exposures precluded differentiation and detailed description of contacts and some other features of map units in the study area.

Franciscan Complex

Franciscan Complex rocks in the study area can be subdivided into coherent sandstone and *mélange*. Other workers have similarly divided Franciscan rocks in the Diablo Range and elsewhere because the units are commonly interpreted to be in fault contact, and probably have vastly different origins (e.g., Cowan, 1974; Blake et al., 1984; Blake and Wentworth, 1999).

Coherent Sandstone

Coherent sandstone crops out along the steeper slopes in the study area, and is generally more resistant than *mélange* units (Fig. 5). Extensive vegetation grows in the sandstone sections (Fig. 5). As a result, exposures of the sandstone are sparse, and are

Figure 5. Topographic expression of Franciscan units. Coherent sandstone underlies the relatively steep slopes in center of photo. Mélangé underlies the area in the foreground of picture. Photo taken looking east; Arroyo Hondo on right edge of picture. One-lane dirt road and car on left edge of photo for scale.

usually not more than a few square meters in area. Still, there are many coherent sandstone outcrops, and lithology is consistent between outcrops.

Most outcrops have extensive moss or lichen growing on them or within fractures, and most rock surfaces are stained with clay and silt. Outcrops with distinct foliation sometimes develop a spheroidal weathering-like appearance that is bounded by foliation and fractures. On broken surfaces, the internal weathering appears minimal. Veins of quartz or carbonate are present but not pervasive, and commonly fill planar fractures that have fairly consistent orientations, but usually are not parallel to bedding or foliation.

Fresh surfaces of the sandstones are generally light green to light brown, are low in lithic fragments, and contain variable amounts of matrix. Increased amounts of matrix and small grain size can obscure grain boundaries. Shale chips up to 0.4 cm long and mica flakes are common and generally parallel to bedding. The sandstones are fine- to medium-grained, poorly to moderately sorted, and subangular to subrounded (Figs. 6 and 7). Rare bedding is defined by siltstone or shale interbeds that are typically less than about 20 cm thick, and commonly less than 10 cm thick. There are also rare beds of very fine- to fine-grained sandstone about 1 cm thick, coarse-grained sandstone, and pebble conglomerate.

Chert

A fault-bounded unit of chert crops out only in the northwestern corner of the map area (Plate 1, A-2, B-2). The eastern contact of this distinctive unit may mark a significant boundary within the study area because to the east there is no chert, and to the

Figure 6. Photomicrograph of a typical poorly-sorted coherent sandstone. Plane-polarized light. Base of photo 6.6 mm.

Figure 7. Photomicrograph of a typical moderately sorted coherent sandstone. This is also an example of a typical Textural Zone 1-2A coherent sandstone. Note the lack of fabric and deformed grains. Plane-polarized light. Base of photo 6.6 mm.

west Franciscan rocks of the Calaveras Creek block are distinctly different in terms of lithology and structure.

The chert is resistant and forms a topographic spine. Chert beds are typically between 0.5 cm and 3 cm thick, and are locally laminated. Chert is light green and locally stained orange, and is interbedded with light green shale that is usually less than 5 mm thick. White quartz veins have variable orientation relative to bedding, are up to 1 cm thick, and are more resistant than the host rock. The chert is locally folded.

Just west of the chert outcrops is a distinct metatuff unit that crops out along a very steep cliff; safe access is only gained along the upslope margin. The metatuff has limited areal extent and may represent the base of the chert. This unit is composed of very hard olive-green and dark blue layers. The dark blue layers probably record recrystallization to sodic amphibole that gives the rocks a banded appearance. It is unclear whether the layering reflects a primary igneous compositional/flow feature or one that was imposed by deformation. The rocks also have an anastomosing cleavage with slickensided surfaces.

Mélange

Mélange matrix and blocks are described separately because they have different lithologic and structural characteristics, and probably have diverse origins, which are discussed in later sections.

Mélange Matrix. The matrix is highly recessive and crops out rarely (Fig. 8).

Large landslides in the study area are concentrated within mélange, demonstrating its instability. Mélange matrix is inferred to underlie gently sloping and/or unstable slopes between ridges or blocks. Compared to coherent sandstone, the matrix is well-bedded (Fig. 9). Some of the best matrix exposures are in roadcuts, and even these reveal at most a few square meters of outcrop (Fig. 8), making it difficult to determine whether sandstone comprises small blocks or is actually interbedded within shale matrix. However, two good exposures, one in a young erosion gully (Plate 1, location 1) and the other in a roadcut (Plate 1, location 2), probably display representative bedding relationships, and provided a total of four samples of sandstone interbeds within the shale matrix (Fig. 9).

The mélange matrix consists mainly of dark gray to black fissile shale with a pervasive sheared, scaly fabric, and lesser amounts of interbedded sandstone. The matrix sandstone generally is restricted to laminated beds less than about 30 cm thick (Fig. 9). Hand samples show some variation in lithic content and amount of matrix. Colors vary from light orange-brown to light greenish-gray. In thin section, the sandstone is moderately sorted (Fig. 10), very fine- to fine-grained, and subangular to subrounded.

Contacts between mélange units and coherent sandstones are not exposed. However, locally there is sufficient exposure to infer that the contacts are sharp and not repeated by faults. One exposure interpreted to represent a contact between mélange and underlying coherent sandstone is expressed at the surface by a quartz vein about 20-30 cm thick (Plate 1, location 2, and Fig. 11). The west side of the vein is cemented

Figure 8. Typical *mélange* outcrop pattern. Although matrix probably underlies most of the area between blocks, it does not crop out in this area. Photo taken looking east, along Oak Ridge Road. One-lane dirt road for scale.

Figure 9. Mélange matrix outcrop. Sheared shale and rare exposure of original sandstone interbeds (along sides of hammer) are preserved. Note that if only a small area of the sandstone in this outcrop were exposed, it would be difficult to be sure it was matrix sandstone (see text). Hammer for scale. Photo taken at location 1.

Figure 10. Photomicrograph of a typical moderately sorted matrix sandstone. Plane-polarized light. Base of photo 6.6 mm.

Figure 11. Coherent sandstone-mélange contact. Outcrop is coherent sandstone (left of line), with a relatively thick quartz vein (right of line) oriented almost vertically. I interpret this vein to lie along a fault contact between coherent sandstone and mélange that modifies the original contact (see text). Hammer for scale. Photo taken looking north, at location 3.

onto coherent sandstone. Host rocks have been completely eroded from its east side, but exotic blocks of chert and greenstone crop out a few meters away, and are evidence of *mélange*. I infer that the quartz vein filled some sort of fracture between *mélange* and coherent sandstone.

Mélange Blocks. Block types in the *mélange* include, in order of decreasing abundance, sandstone, greenstone, chert, blueschist, amphibolite, conglomerate, and intrusive igneous rocks. Blocks range in diameter from about 10 cm or less up to about 150 m (Fig. 12). Most blocks are less than about 10 m across (Figs. 8 and 12).

A distinctive characteristic of *mélange* is its outcrop pattern. *Mélange* blocks crop out at the surface of gently sloping grassy hillsides, usually showing more erosional resistance than surrounding matrix (Figs. 8 and 12) regardless of block type. The random distribution of blocks at the surface most likely reflects the block distribution within the matrix. Almost all contacts with the enclosing matrix are obscured by vegetation (Figs. 8 and 12), but two outcrops are particularly revealing. A hillside outcrop exhibits a greenstone block in contact with shaly matrix. The second is a conglomerate block in contact with shaly matrix (Plate 1, location 4, and Fig. 13). The conglomerate outcrop is described in more detail in the structure section of this report.

Origins of the blocks are unclear. Many of them represent source terranes that are not presently exposed, and may not be genetically related to the matrix, especially the high-grade metamorphic blocks. The metamorphic assemblages in individual blocks

Figure 12. View of largest mélangé block in study area (within line). Photo also shows another view of typical outcrop pattern of mélangé. All outcrops in view are mélangé blocks. The large block is a greenstone block, and is overlain by red chert. Photo taken looking west, from Oak Ridge Road. One-lane dirt road for scale.

Figure 13. Mélangé block-matrix contact. Outcrop of a conglomerate mélangé block in contact with mélangé matrix shale. Note the lenticular shape of block, increased shearing toward its contacts with matrix, and matrix that wraps around the block margins. Hammer for scale. Photo taken at location 4.

range from pumpellyite-prehnite facies to amphibolite facies, indicating that the *mélange* reflects source areas with different histories and tectonic settings.

Sandstone Blocks. Sandstone *mélange* blocks are the most abundant type of block in the study area, and they display a wide range of lithologies and textures. However, roughly half of the sandstones with a *mélange*-block outcrop pattern resemble the adjacent coherent sandstone and *mélange* matrix sandstone units in grain size, color, and abundance of lithic fragments. Cowan (1974) and Worrall (1981) also noted this type of field relationship.

The resistant *mélange*-block outcrop pattern, typical of blocks of any type (as described above), is the most reliable characteristic for distinguishing sandstone blocks from an adjacent coherent unit or *mélange* matrix. When field relations were unclear, I occasionally used veins, common in *mélange* blocks, to distinguish a sandstone block from coherent sandstone. Veins in *mélange* blocks are randomly oriented, and fill irregularly shaped voids in the rock; in contrast, rather than, such those occurring in coherent sandstones have roughly planar fractures with a consistent orientation. Also, some smaller sandstone blocks appear to have weaker foliation than the coherent sandstones. Blocks that showed the wide diversity of the lithologic variations were sampled more frequently.

Greenstone and Chert Blocks. Blocks of greenstone and chert are often found near one another at the study area. The greenstones are aphanitic, light to dark olive-

green on fresh surfaces, and distinctly dark brown to brownish-red on weathered surfaces. Weathering and fracturing are commonly pervasive, making it difficult to observe a fresh surface and diagnostic lithology. Fractures are apparently randomly oriented, and commonly are closely spaced. Quartz and calcite veins are also common.

The largest *mélange* block in the field area consists of greenstone overlain by red ribbon chert (Plate 1 and Fig. 12). Three smaller blocks also consist of this sequence (Plate 1), and one contains the sequence greenstone, chert, sandstone.

Chert blocks are common in the *mélange*, and are usually well-bedded, and red, white, or green. Beds typically are 1 to 5 cm thick, and are separated by thinner, less-resistant shale interbeds.

Blueschist and Amphibolite Blocks. Blueschist blocks are widespread in *mélange* in the study area, but only a few are large enough to show at map scale. Blueschist blocks range in texture from foliated to massive. All consist mainly of fine-grained sodic amphibole, with variable amounts of mica and quartz. Individual Na-amphibole crystals are not visible to the unaided eye. The more micaceous blueschist blocks generally are lighter blue in color and have pronounced foliation and lineation. Quartz-rich blocks are darker in color and harder. Within any given block, textures are highly variable due to shearing and veining. The more deformed a block is, the more veins it typically has.

Five amphibolite blocks were identified in the study area. In hand sample the rocks are very hard and fine-grained, and contain abundant black, bladed amphibole. Parts of the rock are more foliated than others, imparting a more schistose appearance.

Quartz and carbonate veins are locally abundant in the more deformed areas. A cut surface of one sample revealed a massive texture with a weak layering defined by alternating segregations of mafic minerals, quartz, and plagioclase. Thin sections show yellow to light-green amphiboles with strong preferred orientation, and some display blue pleochroism probably due to Na replacement. There are minor amounts of polycrystalline quartz and highly altered plagioclase, and rare late metamorphic lawsonite. No other lithologic or petrologic analyses of these rocks were undertaken.

Conglomerate Blocks. Five conglomerate blocks were identified in the study area (Plate 1). They are clast-supported, and consist of pebble- to cobble-sized sub-angular to sub-rounded clasts of chert, sandstone, and volcanic, plutonic, and metamorphic rocks. No clast counts were undertaken, but the conglomerates lack obvious Franciscan-like clasts such as blueschist, red chert, or matrix-rich sandstones.

Intrusive Igneous Blocks. Four plutonic *mélange* blocks were identified in the study area, and are described here in detail because their lithologies and modes of origin are distinctive within the *mélange*. These rocks are best described from slab surfaces and thin sections due to variable degrees of deformation and weathering that largely obscure igneous texture in hand sample. Sample locations are shown on Plate 1.

Sample 69 is a fine-grained, leucocratic, hypidiomorphic, porphyritic, plagiogranite, with about 5% tabular subhedral plagioclase phenocrysts that are about 0.5 x 1.0 mm on average, but up to 1.1 x 1.6 mm, in an equigranular groundmass of about

70% tabular subhedral plagioclase laths that are about 0.15 x 0.3 mm on average. The rest of the rock is interstitial anhedral quartz. The plagioclase has common albite twinning and some Carlsbad twins. There is moderate alteration of plagioclase to sericite, and metamorphic lawsonite. Interlocking grains are abundant, and grain-boundary suturing is common, so some plagioclase is anhedral (Fig. 14). The primary igneous texture of this sample is variably disrupted by crystal plastic deformation of quartz and some cataclasis of feldspar (Fig. 14).

Sample 121 is a fine-grained, melanocratic, hypidiomorphic, equigranular gabbro, with about 15-20% tabular subhedral plagioclase that is about 0.8 x 1.0 mm on average, but up to 4 x 5 mm. Most of the rest of the rock is prismatic, subhedral, clinopyroxene that is about 0.8 x 0.8 mm on average. Plagioclase has common albite twins, is commonly replaced by lawsonite, and is mildly altered. Most primary igneous textures have been obscured by intense alteration and grain-size reduction by cataclasis, but plagioclase-clinopyroxene intergrowths are locally preserved (Fig. 15).

Sample 116 is a fine-grained, mesocratic, hypidiomorphic, hornblende gabbro with about 40% tabular subhedral to anhedral plagioclase that is about 0.6 x 0.6 mm on average, but up to 1.5 x 2.0 mm. The rest of the rock is prismatic, subhedral to anhedral, green to light brown calcic amphibole that is about 0.35 x 0.5 mm on average, but up to 2.75 x 4 mm. The plagioclase has both albite and Carlsbad twins, is replaced by lawsonite, and is extensively altered. Plagioclase is locally enclosed in amphibole (Fig. 16), and has a heterogeneous distribution throughout the rock. There are abundant

Figure 14. Photomicrograph of plagiogranite mélange block texture (sample 69). At center of view is a plagioclase phenocryst, surrounded by plagioclase and quartz. Fine-grained tabular mineral is lawsonite (arrows), replacing plagioclase. Crossed polars. Base of photo 3.3 mm.

Figure 15. Photomicrograph of gabbro mélangé block texture (sample 121). At center of view is a plagioclase lath intergrown with clinopyroxene, and other intergrowths are also visible. Note the band of broken grains along the right-hand side and across the bottom. Some lawsonite (arrow) grains replacing plagioclase are visible in upper right corner. Crossed polars. Base of photo 6.6 mm.

Figure 16. Photomicrograph of gabbro mélangé block texture (sample 116). This view shows intergrown plagioclase and amphibole. Fine-grained tabular minerals are lawsonite (arrows) replacing plagioclase. Crossed polars. Base of photo 3.3 mm.

interlocking grains, and possible relict poikilitic texture. Some amphiboles have been partially replaced by blue, probably Na-rich, amphibole (Fig. 17).

Sample 76 is a fine-grained mesocratic equigranular gabbro, with 20-30% tabular subhedral to anhedral plagioclase that is about 0.35 x 0.8 mm on average, but up to 0.9 x 2.6 mm. The rest of the rock is composed of anhedral light-green chlorite that is about the same size as the plagioclase. Chlorite has an anomalous blue interference color, and probably has replaced pyroxene and/or amphibole. Plagioclase has common albite twins and some Carlsbad twins. Plagioclase is locally replaced by lawsonite, and moderately to extensively altered to sericite and chlorite. This rock has some interlocking of smaller plagioclase grains with chlorite host grains (Fig. 18). Minor carbonate veins are present.

All four of the previous samples have ophitic texture. This confirms the igneous origin for these rocks, but the texture is also significant because it is characteristic of dikes and sills of basic composition. The plagiogranite has a porphyritic texture typical of intrusion at a shallower level.

Calaveras Creek Block

The Calaveras Creek block is located near the intersection of Alameda and Calaveras creeks (Plate 1, A-1, A-2, B-1, B-2). These rocks are not part of coherent sandstone or *mélange* from the rest of the study area, but they may be part of a fault-bounded fragment of some other coherent unit within the northwestern Diablo Range. Rocks in the Calaveras Creek block are significantly different from others in the field area in that the metamorphic grade is higher, and, judging from the presence of different

Figure 17. Photomicrograph of amphibole replacement. Amphibole at center of view shows blue pleochroism in the middle of the grain, indicating partial replacement by Na-amphibole. Plane-polarized light. Base of photo 3.3 mm.

Figure 18. Photomicrograph of gabbro mélangé block texture (sample 76). At center of view is a plagioclase phenocryst. Anhedral mineral with anomalous blue interference color is chlorite. Note how chlorite host grains appear intergrown with plagioclase phenocryst and smaller plagioclase grains on the sides of the picture. Some of the fine-grained minerals are lawsonite (arrows) replacing plagioclase. Crossed polars. Base of photo 3.3 mm.

rock types within a small area, the structures are more complex. The Calaveras Creek block is a structural group of rocks with slivers of metabasalt and possibly metatuff, sandstone, and *mélange*. Chert includes outcrops similar to the main body described above (Plate 1, A-2, B-2), and a different variety that is described below. Few contacts are exposed (Fig. 19), so the overall structure is not fully understood.

A sharp, steeply dipping contact between tectonically interleaved greenstone and sandstone marks the westernmost part of the ridge near Calaveras Creek (Fig. 19). The metabasalt is olive-green and locally brecciated. The metabasalt is dark blue from recrystallization to sodic amphibole along locally abundant fractures and strong foliation. The metabasalt is locally tuffaceous, and is cut by carbonate veins. The sandstone is strongly foliated and, judging from thin sections of similar sandstone in the Calaveras Creek block, almost totally recrystallized. The sandstone contains minor quartz veins parallel to foliation.

Sandstone and chert crop out throughout this block, but they only occur together in one small outcrop (< 10 m across) in Alameda Creek, where the two units are interbedded (Plate 1, location 5, and Fig. 20). The chert has alternating light bluish-green layers and white quartz layers that are between 0.5 and 2 cm thick. The quartz layers are discontinuous and disharmonically folded. The sandstone is very fine- to fine-grained, strongly foliated, nearly entirely recrystallized, and extensively veined parallel to foliation. Some veins are isoclinally folded with the axial planes parallel to foliation. The outcrop consists of basal sandstone overlain successively by 15 cm of chert, 7 cm of sandstone, and at least 2 m of chert, but the top of the chert is unexposed. Contacts are

Figure 19. Main ridgeline in Calaveras Creek block. Large outcrop at west end of ridgeline is interleaved Franciscan Complex greenstone and sandstone. Arrow indicates approximate location of outcrop of Temblor Sandstone at location 6 on Plate 1. View looking northeast.

Figure 20. Interbedded chert-sandstone outcrop. Light-colored rock is chert, dark gray rock is sandstone. Note that the layers thin toward the left, and contacts are wavy. Hammer for scale. Photo taken at location 5.

sharp and wavy, but locally gradational (Fig. 21). The units do not maintain constant thickness across the outcrop. The thin sandstone interbed contains some cm-scale cherty layers that are possibly boudinaged, although these may be quartz veins rather than chert. In a nearby outcrop, chert and sandstone are interleaved on a centimeter scale (Fig. 22). Depositional environments of chert and sandstone are discussed in the last chapter of this report.

Age

No fossils have been recovered from the Franciscan Complex in the study area. In similar coherent sandstone several kilometers south of the study area, a single specimen of the Tithonian (152-144 Ma) *Buchia fisheriana* was identified (first cited in Cotton, 1972). Elder and Miller (1993) have since more precisely determined the age of that fossil as 147-145 Ma. Sliter et al. (1993) and Isozaki and Blake (1994) cite data stating that chert from the Yolla Bolly terrane of the Diablo Range is late Early to Middle Jurassic (Fig. 2).

Claremont Chert and Temblor Sandstone

The Temblor Sandstone overlies the Franciscan Complex in the southwestern part of the study area (Plate 1, B-1, B-2, C-1, C-2, D-2), and is locally conformably overlain by Claremont Chert of the Monterey Group. The Temblor overlies the Franciscan along a fault, as mapped by Graymer et al. (1996), and is depositional in quarry and roadcut exposures across Calaveras Creek to the southwest. Here, Graymer et al. (1996) mapped

Figure 21. Interbedded chert-sandstone outcrop. Close-up from same outcrop as Figure 20. Note that the lower contact is sharp, but the upper contacts near the center of the photo are gradational. Also note folding in chert and veins in sandstone. Pencil for scale. Photo taken at location 5.

Figure 22. Interbedded chert-sandstone outcrop. Photo from same outcrop as Figures 20 and 21. Bottom of photo is sandstone, and top is chert. Near the center of the photo (just left of pencil) is a zone where the chert and sandstone are interlayered at a centimeter scale. Pencil for scale. Photo taken at location 5.

a depositional contact between Temblor Sandstone and Franciscan Complex rocks that are similar to some in the Calaveras Creek block.

The Temblor Sandstone in the study area consists of light yellowish-brown, well-bedded to massive, fine- to medium-grained arkosic sandstone, local pebble conglomerate beds with well-rounded clasts, and distinctive 5- to 10-cm-thick beds that contain abundant fragments of brachiopods (Plate 1, location 7). Crittenden (1951) noted that the conglomerate and fossiliferous beds are towards the base of the section, and that the whole section in this area is probably between about 152 to 300 m (500 to 1000 ft) thick. The Claremont Chert in the study area is composed mostly of white to buff, laminated siliceous mudstone. Both formations are early to middle Miocene (Crittenden, 1951; Graymer et al., 1996).

Quaternary Deposits

Quaternary deposits in the study area include boulders along the reservoir margins, stream deposits in Alameda Creek, old alluvium, and landslide deposits. I mapped the landslide deposits (Fig. 23) in the field and with aerial photographs. I did not make an effort to comprehensively map landslides in the study area, but I mapped ones that were clearly evident, and those that could potentially affect interpretation of the bedrock structure. Active landslides are not distinguished from dormant slides in Figure 23. Dibblee (1973) mapped some large landslides, Nilsen et al. (1975) mapped extensive landslides around Calaveras Reservoir, primarily using aerial photographs, and Wentworth et al. (1999) compiled large landslides previously mapped by Nilsen and

Figure 23. Landslide map. Active landslides are not distinguished from dormant slides, but the active slides are generally smaller. Large slides are complexes of separate slides. Abbreviations of geologic units are from Plate 1.

Dibblee. Some landslides that I have mapped coincide with those mapped by these previous workers, but I did not compile their results on my map.

Many of the large landslides I mapped have subdued features and thus appear to be dormant, yet they maintain a distinct topographic expression that makes them easily identifiable. Few landslides in the study area are currently active, and they typically have limited aerial extent and do not involve bedrock. Fresh scarps and well-defined margins usually define active landslides. Dormant landslides are distinguished by relatively subdued features, dissection by streams, and mature vegetation, such as large trees, within their margins. Several of the large landslides I mapped are complexes that may include both dormant and active slides. The larger slides generally are more likely to involve bedrock than smaller ones. The largest landslide complexes typically occur within *mélange*.

Sandstone Point Counts

Seventeen thin sections of Franciscan Complex sandstone were point-counted with 400-500 points per slide, at 1 mm intervals, and 100x magnification. I completed point counts on an Olympus BHA petrographic microscope, using a Brinkman Instruments counter with a J. Swift & Sons electronic stage advance. A QFL ternary diagram was used to plot detrital modes. Q includes monocrystalline and coarsely polycrystalline quartz grains excluding chert. F includes monocrystalline feldspar. L includes all igneous, sedimentary, metamorphic, chert, and detrital mica grains. These parameters are similar to those of Dickinson (1970b), but the high degree of alteration in

the rocks of this study precludes strict adherence to his parameters. The most significant difference from the methods of Dickinson (1970b) is my inclusion of chert in L instead of Q. This was done because chert is often difficult to consistently distinguish from some volcanic grains due to the alteration in these rocks. Additionally, categorization of different types of lithic grains was often impossible. Jacobson (1978) and Jayko et al. (1984) noted similar difficulties.

Including chert with L is the only variation that would affect comparison of my modal compositions with others who have included chert with Q, so I counted chert as a separate grain type for ease in compiling QFL data using either method. Nevertheless, I counted so few chert grains (Appendix) that the difference in methods is nearly insignificant for my data.

I selected samples that were representative of the main geologic units in the study area (Plate 1). At least one thin section was made from each coherent sandstone body sampled in the field. For *mélange* blocks, I thin-sectioned samples that seemed to represent the range of different sandstone compositions and textures I observed in the field. For *mélange* matrix, I thin sectioned samples that were unquestionably *mélange* matrix. Samples that were questionably *mélange* matrix were also thin-sectioned to investigate whether compositions were diagnostic of the rock units. Within the groups of *mélange* blocks and *mélange* matrix samples, several thin sections were disqualified from point-counting because they are either too recrystallized, or too fine-grained to yield accurate results. Point counts from the various coherent sandstone map units plot within

such a small range on the QFL diagram that they were judged unlikely to permit differentiation of units based on petrology.

A representative group of 25 hand samples was stained for potassium feldspar using modified techniques of Norman (1974), and then inspected under a Leitz paleontologic microscope at 50x magnification. None of the samples picked up stain, so no thin sections were stained for potassium feldspar. The staining technique and the stain mixture were tested for effectiveness on a coarse-grained granitoid, rich in potassium feldspar. Several authors have noted the scarcity of potassium feldspar in many Franciscan Complex sandstones (e.g., Jacobson, 1978; Dickinson et al., 1982; Jayko and Blake, 1984).

Aragonite can be difficult to optically differentiate from calcite, so samples that contained carbonate veins were stained for aragonite using Meigen's reaction. Seven of seventeen samples stained positive for aragonite. The stain results were compared with observations of aragonite in the corresponding thin sections to test for effectiveness of the stain, and to better recognize aragonite optical properties.

Sources of Error

The effects of diagenetic alteration and metamorphic recrystallization made identification of some feldspars and many lithic fragments difficult, and in some cases impossible. Often, indirect evidence had to be used to identify a particular detrital grain. For example, a grain hosting abundant fine-grained actinolite, a Ca-amphibole, probably would be counted as a plagioclase grain.

Another source of error involved the distinction of some feldspar grains from volcanic grains. Through some alteration process, many feldspars have developed a polycrystalline texture that can obscure twinning and other properties that aid in its identification (Fig. 24). A significant number of feldspars could be miscounted if this texture is not recognized. This texture is distinct from chessboard albite, which is a texture formed by albite replacement of potassium feldspar (Fig. 25; Moore and Liou, 1979; Walker, 1984).

Significantly altered detrital grains commonly have more than one stable phase (e.g., pumpellyite and chlorite), and it is difficult to tell if any phases were present in the grains prior to deposition. Grains that contain pumpellyite, chlorite, actinolite, and lawsonite, which are stable under blueschist-facies conditions, may be detrital metamorphic grains that were subjected to similar post-deposition metamorphic conditions, and did not develop an assemblage distinct from the host rock.

I interpreted such relationships based on comparison with similar grains observed in the rock. A sample might have a common metamorphic assemblage or texture for a specific grain type, which was compared to questionable grains. That was not always possible, however, because these rocks are generally less than 15-20% recrystallized.

Most of the error probably affected values of the various types of lithic fragments, but this would not affect overall modal compositions. Generally, the QFL data reported herein are quite similar to published data on Franciscan sandstones within the northern Diablo Range, and the Franciscan as a whole (e.g., Jacobson, 1978; Jayko and Blake, 1984).

Figure 24. Photomicrograph of feldspar alteration texture. Feldspar grain at center of view has a heterogeneous alteration texture that causes the grain to appear polycrystalline. Crossed polars. Base of photo 1.32 mm.

Figure 25. Photomicrograph of chessboard albite. Feldspar at center of view has chessboard twinning. This texture is thought to represent K-spar that has been at least partially replaced by albite. Note the twin planes at right angles to each other, compared to grain on left side of photo. Crossed polars. Base of photo 1.32 mm.

Franciscan Complex QFL Data

Detrital modes of selected Franciscan Complex sandstones were compiled to aid lithologic description, potentially help differentiate map units, and compare my results with data reported by others. Correlations based on my QFL data are discussed in the last chapter of this report.

All of the data plot within a small field centered at $Q_{28} F_{49} L_{23}$ (Fig. 26). The main compositional difference within the groups is modal percentage of F and L. The coherent sandstones have the least internal variation and the *mélange* block group has the most. No samples contain potassium feldspar, and chert grains are present only in trace amounts (Appendix).

The coherent sandstone F and L components vary by up to 18%, and vary significantly in the number of volcanic grains and the amount of matrix (Appendix). Some coherent sandstone samples contain appreciable amounts of blueschist-facies detritus (Fig. 27). Coherent sandstones generally have more Q_p and higher matrix content than other sandstones.

Matrix sandstones have a maximum variation of 22 modal percent within F and L, and vary considerably in the amounts of volcanic lithic fragments. Matrix sandstones average the most monocrystalline quartz, and they would also average the least amount of Q_p except for one sample that contains anomalously high amounts. The average *mélange* matrix sandstone and coherent sandstone have very similar compositions.

Sandstone *mélange* block samples plot along a line generally parallel to the bottom axis of the QFL diagram, within the same field as the other units. There is a

Figure 26. QFL diagram. Modal percentages from point counts of this study. Sandstone is abbreviated with ss.

Figure 27. Photomicrograph of blueschist detritus (sample 36). Detrital lawsonite/white mica pair at center of view. Note rounding of the grain, and the broken fragment just beyond top edge of the grain (arrow). Crossed polars. Base of photo 1.32 mm.

maximum variation of 32 modal percent within L. Two samples—the coarsest-grained of all point-counted samples—contain relatively large amounts of volcanic and metamorphic detritus. Some metamorphic detritus is blueschist-facies (Fig. 28). Except for the one sample with relatively high lithic content, the *mélange* blocks also plot within the same compositional field on the QFL diagram.

These data show that sandstones from the three lithologic groups are essentially indistinguishable from each other in terms of modal composition. Also, samples from each of the coherent map units have very similar composition.

Figure 28. Photomicrograph of blueschist detritus (sample 67). Largest detrital grain in view contains abundant greenish-yellow, fine-grained jadeite. Note that jadeite does not extend beyond the sharp grain boundary. Plane-polarized light. Base of photo 1.32 mm.

METAMORPHISM

Many Franciscan Complex samples from the field area contain the blueschist-facies index minerals lawsonite, jadeite, or aragonite. Coherent sandstones contain widespread lawsonite and rare jadeite, and are typically only slightly recrystallized. Mélange matrix sandstones contain rare lawsonite, and are generally less recrystallized than the coherent sandstones. Most mélange blocks are also blueschist-facies, but facies can range from prehnite-pumpellyite to amphibolite, and the degree of recrystallization is highly variable. Some blueschist metamorphic minerals described in this chapter are detrital grains, and their significance will be discussed in the last chapter of this report.

Blueschist Mineralogy

The following sections describe the optical characteristics of blueschist-facies minerals in the study area.

Lawsonite

Lawsonite ($\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 2\text{H}_2\text{O}$) is present within almost every sandstone and plutonic rock sample that was examined in thin section for this study. The lawsonite occurs mostly as fine-grained, idioblastic, tabular crystals replacing Ca-rich plagioclase grains (Fig. 29), and less commonly forms fine-grained, needle-like masses. Most crystals are less than 0.1 mm in length. Lawsonite is distinguished in thin section by

Figure 29. Photomicrograph showing lawsonite (arrows) properties. Note the tabular form and high positive relief. This view also displays the typical amount of recrystallization in the coherent sandstones of this study, and typical size of lawsonite grains. Plane-polarized light. Base of photo 1.32 mm.

its high positive relief, euhedral form, good cleavage, and low second-order birefringence (Figs. 29 and 30).

Lawsonite crystals occur in several settings in replacement of plagioclase. Most commonly they are apparently randomly oriented within the host grain, and in some cases they seem to have grown inward from the edge of the grain. In one sample a few individual lawsonite grains are parallel to plagioclase twin lamellae (Fig. 31). In some rocks, certain plagioclase grains are extensively recrystallized to lawsonite, while other grains contain no lawsonite. This could either be the result of variations in the amount of Ca within plagioclase grains, or reflect reaction kinetics. In general, the abundance of lawsonite increases with textural grade.

Lawsonite was also found within various igneous and sedimentary lithic fragments that presumably contain plagioclase (Fig. 32). In most of these cases the lawsonite is very fine-grained, but in some coarse-grained igneous grains the lawsonite is relatively coarse-grained.

Intergrown lawsonite and metamorphic white mica are widespread within the interstitial matrix of sandstones. This pair mostly occurs in trace amounts but certain samples contain relatively large amounts. Lawsonite that is intergrown with mica typically is coarser-grained and has higher birefringence than lawsonite in other settings (Figs. 33 and 34). Several samples have rounded but obviously broken fragments of intergrown lawsonite and mica that are detrital (Fig. 27).

Lawsonite can also be intergrown with jadeite, another blueschist-facies index mineral (see below).

Figure 30. Photomicrograph showing lawsonite properties. Same view as Figure 31. Note the low second-order birefringence of lawsonite (arrows). Crossed polars. Base of photo 1.32 mm.

Figure 31. Photomicrograph showing lawsonite replacement texture. The plagioclase grain in the center of view is almost wholly replaced by lawsonite grains, some of which appear to have grown parallel to plagioclase twin lamellae. Photo from highly recrystallized sandstone *mélange* block. Crossed polars. Base of photo 1.32 mm.

Figure 32. Photomicrograph showing lawsonite replacement texture. Abundant fine-grained lawsonite replacing the lithic fragment at center of view. Note lawsonite crystal crossing grain boundaries at the right-hand edge of the lithic fragment (arrow), indicating that metamorphism is post-depositional. Plane-polarized light. Base of photo 1.32 mm.

Figure 33. Photomicrograph of intergrown metamorphic lawsonite-white mica (arrow). Note the length relative to detrital grains, and to other lawsonite grains in view. Plane-polarized light. Base of photo 1.32 mm.

Figure 34. Photomicrograph of intergrown metamorphic lawsonite-white mica. Same view as Figure 33. Note the high birefringence of the lawsonite relative to other lawsonite grains in view. Crossed polars. Base of photo 1.32 mm.

Jadeite

Jadeite ($\text{NaAl,FeSi}_2\text{O}_6$) is found only in scattered sandstone samples (Fig. 35).

The abundance of jadeite in these samples generally increases with textural grade.

Jadeite commonly forms coarse-grained, bladed, granular masses that have replaced individual Na-rich plagioclase grains (Fig. 36). Jadeite is distinguished in thin section by its anomalous blue interference color, rolling extinction, moderately high positive relief, and bladed habit (Fig. 37).

Well-developed, coarse-grained jadeite is limited primarily to the Calaveras Creek block, where sandstones are generally more recrystallized than in other areas. Some of these rocks are nearly entirely recrystallized (Figs. 38 and 39). Such jadeite typically is granular and commonly forms large interlocked masses that have probably grown beyond the original size of the host grain (Fig. 40). Once recrystallization reaches this stage, the host rock texture is usually destroyed. Abundant polycrystalline quartz released by the breakdown of albite $\rightarrow$ jadeite + quartz further destroys original textures (Fig. 39).

Elsewhere in the study area, jadeite forms small clusters of fine-grained, needle-like masses that nucleate within plagioclase grains (Figs. 41 and 42). These masses probably represent an incipient stage of jadeite crystallization.

The bladed and acicular forms of jadeite each can be associated with lawsonite. Lawsonite associated with incipient jadeite is also fine-grained and probably in its early growth stages as well (Fig. 41). Coarser-grained lawsonite is commonly observed within and around coarse-grained granular jadeite (Fig. 42), but its abundance does not increase with increasing amounts of jadeite.

Figure 35. Index map of aragonite and jadeite in the study area. Locations correspond to sample locations on Plate 1. Abbreviations of geologic units are from Plate 1.

Figure 36. Photomicrograph showing jadeite properties. Coarse-grained jadeite at center of view. Note the bladed habit, and smaller lawsonite grains (arrows). Plane-polarized light. Base of photo 1.32 mm.

Figure 37. Photomicrograph showing jadeite properties. Same view as Figure 36. Note the distinctive blue interference color and rolling extinction of jadeite. Crossed polars. Base of photo 1.32 mm.

Figure 38. Photomicrograph of highly recrystallized and deformed sandstone. Pale greenish yellow grains are jadeite (arrows). Note that the fabric orientations are slightly irregular. Also note that some of the jadeite grains appear broken, indicating syn- and/or post-metamorphic deformation (see text). Plane-polarized light. Base of photo 1.32 mm.

Figure 39. Photomicrograph of highly recrystallized and deformed sandstone. Same view as Figure 38. Low birefringent material is mostly metamorphic polycrystalline quartz, a product of the jadeite-forming reaction. Note that there is also some monocrystalline quartz, which is probably detrital (see text). This sandstone is TZ 2B, and has extensive jadeite. Mica, insoluble phases, and flattened quartz grains define foliation in the rock. Crossed polars. Base of photo 1.32 mm.

Figure 40. Photomicrograph showing jadeite replacement texture. Large mass of intergrown jadeite grains. Plane-polarized light. Base of photo 1.32 mm.

Figure 41. Photomicrograph showing jadeite replacement texture. Jadeite occurs as small clusters of needles nucleating around lawsonite (arrows). The jadeite is probably in its incipient growth stage, which is common within coherent sandstones that contain jadeite. Plane-polarized light. Base of photo 1.32 mm.

Figure 42. Photomicrograph showing jadeite replacement texture. This incipient jadeite grain (arrow) is at a more advanced growth stage than those in Figure 41. The fine-grained blades are starting to show the radiating structure found in coarser-grained samples such as in Figure 36. Lawsonite is also visible, identified by its tabular form and high positive relief. Plane-polarized light. Base of photo 1.32 mm.

Aragonite

Sparse aragonite (CaCO_3) is present in veins and amygdules in Franciscan Complex sandstones in the study area (Fig. 35). Aragonite was identified in four thin sections of stained samples by the presence of coarse-grained, blocky, optically continuous carbonate grains that are variably replaced by fine-grained calcite along cleavage and/or twin planes.

Textural Zone Classification

Textural Zone (TZ) classifications by Blake et al. (1967) in northern California were the first to be used in the Franciscan Complex. They provide a convenient way to classify and describe deformation in these types of sandstones by using both megascopic and microscopic textures and metamorphic minerals. Subsequently, others have adopted this format to describe Franciscan sandstones in northern California (e.g., Worrall, 1981) and in the Diablo Range (e.g., Ernst, 1971a, 1993; Wentworth et al., 1999). Jayko et al. (1986) proposed a system based on the original by Blake et al. (1967), with more subdivisions and better-defined criteria for classification. I use the Jayko et al. (1986) system for the sandstones in this study. Samples that are transitional between 1 and 2A are labeled TZ 1-2A.

Coherent Sandstones

Coherent sandstones in the study area have a narrow range of textural development, typically within TZ 1-2A. Clastic texture is clearly visible in both hand

sample and thin section. In hand sample, most of the rocks show at least incipient cleavage, and the more well-developed foliation in TZ 2A rocks is commonly spaced about 3-6 cm apart (Fig. 43). The foliation is commonly defined by alignment of fine-grained white mica, which are mostly metamorphic. Foliation is commonly oriented subparallel to bedding and shale chips.

In thin section, TZ 1-2A samples display no grain flattening or other structural fabric, but they do contain metamorphic lawsonite (Fig. 7). TZ 2A samples have a weak but obvious structural fabric, and foliation planes are defined mainly by insoluble phases within the matrix, flattened grains, and by minor metamorphic mica (Fig. 44). TZ 2A samples also contain lawsonite, and a few contain jadeite in its incipient growth stage (Figs. 41,45, 46). The system of Jayko et al. (1986) includes jadeite in its mineralogic criteria for TZ 2B, but not for TZ 2A. Nevertheless, the textural properties of the samples with jadeite are consistent with TZ 2A, and the small amount of jadeite present in these samples does not warrant classifying them as TZ 2B.

Calaveras Creek Block

Some fine-grained TZ 2B sandstones crop out in the Calaveras Creek block. In outcrop, they exhibit a strong foliation that is parallel to bedding (Fig. 47), and retain clastic texture. The sandstones are highly recrystallized, and plagioclase has been almost totally replaced by jadeite (Fig. 39), but the presence of monocrystalline quartz is evidence that the rocks are not completely recrystallized. Micas are larger than those in the coherent sandstones and, together with insolubles and flattened grains, define

Figure 43. Coherent sandstone outcrop. Note the spaced foliation that dips gently to the right. Hammer for scale.

Figure 44. Photomicrograph of a typical TZ 2A coherent sandstone. The fabric is defined by insoluble phases and flattened grains. Plane-polarized light. Base of photo 6.6 mm.

Figure 45. Photomicrograph of a typical TZ 2A coherent sandstone. This rock has incipient jadeite (arrow). The sample also contains lawsonite. The relatively low degree of recrystallization is typical of the coherent sandstones in this study. Plane-polarized light. Base of photo 1.32 mm.

Figure 46. Photomicrograph of a typical TZ 2A coherent sandstone. Same view as Figure 45. The rolling extinction pattern of the grain in the center of view confirms this grain is jadeite (arrow). The slide is slightly thin, so birefringence is low. Crossed polars. Base of photo 1.32 mm.

Figure 47. Sandstone bedding. Contact of TZ 2B sandstone and mudstone beds. Planar base of sandstone overhang is parallel to bedding and foliation. Hammer for scale. Photo taken near location 5 on Plate 1.

the fabric in the rock. The texture is locally planar, but not pervasively so, as pictured in the example of TZ 2B sandstones in Jayko et al. (1986) (Fig. 38). However, extensive jadeite is present, so I classify these sandstones as TZ 2B.

Stability of Index Minerals

Lawsonite

Lawsonite is stable at lower pressure than aragonite and jadeite (Liou, 1971) (Fig. 48). Its temperature stability is less well-constrained because of sluggish reactions and the dependence on reaction assemblages within a given sample. Temperatures for the lawsonite-zoisite reaction (curve 2 in Fig. 48) may not have widespread significance, but they probably provide a maximum temperature. Brown (1977), Brown and Ghent (1983), and Maruyama and Liou (1987) have modeled lawsonite-consuming reactions that suggest the breakdown of lawsonite occurs between 225 and 300°C, depending on the reaction assemblages and local conditions.

Jadeite

Sodic clinopyroxene contains the solid solution endmembers jadeite (Jd_{100} — $\text{NaAlSi}_2\text{O}_6$), and aegirine (Jd_0 — $\text{NaFeSi}_2\text{O}_6$). Increasing Al content in jadeite corresponds to a higher pressure of recrystallization (Fig. 48). Sodic clinopyroxene in rocks correlated with or petrologically similar to some of those in my study area consistently has yielded jadeite compositions in excess of Jd_{60-70} (Coleman, 1961; Kerrick and Cotton, 1971; Sedlock, 1988; Ernst, 1993).

Figure 48. Pressure-temperature diagram. Reaction curves for metamorphic minerals found in meta-sandstones in the study area are compiled. Shaded area covers the approximate P-T field of coherent sandstones and matrix sandstones in the study area. Mineral abbreviations: Lw—lawsonite, Zo—zoisite, Cal—calcite, Arag—aragonite, Jd—jadeite, Ab—albite. References for reaction curves: (1) Liou, 1971; (2) Nitsch, 1968 and 1971; (3) Brown and Ghent, 1983; (4) Crawford and Hoersch, 1972 below 150°C, and Johannes and Puhon, 1971 for higher temperatures; (5) Newton and Smith, 1967; (6) Nitsch, 1968 and 1971; (7) Brown, 1977; Brown and Ghent, 1983; Maruyama and Liou, 1987.

Ernst (1993) notes that the breakdown of albite to form jadeite + quartz can be a sluggish reaction. The non-systematic Jd_x distribution and metastable albite within metagraywackes in the Pacheco Pass quadrangle led Ernst (1993) to suggest that jadeite-producing reactions are driven more by reaction kinetics than by P-T conditions. Thus, metamorphic conditions based on Jd_x may not represent actual peak pressures because many samples near Jd_{100} coexist with samples that have lower Jd_x and metastable albite (Ernst, 1993).

Aragonite

Aragonite is stable at pressure-temperature conditions roughly intermediate between those of lawsonite and jadeite (Fig. 48). Aragonite rapidly inverts to calcite when depressurization occurs above 175°C (Carlson and Rosenfeld, 1981), constraining pressure-temperature conditions following peak metamorphism.

Metamorphic Conditions

Many previous workers in the Franciscan Complex of the Diablo Range and elsewhere have used lawsonite, jadeite, and aragonite to estimate the conditions and tectonic setting of metamorphism (e.g., Ernst, 1970; Maruyama et al., 1985; Ernst, 1993). I combine my results with previous work on similar rocks elsewhere to estimate metamorphic conditions of the coherent sandstones and mélangé matrix units in my study area.

Peak P-T Conditions

The stable association of lawsonite and aragonite indicates a minimum pressure of about 5 kb. The presence of lawsonite, jadeite, and aragonite constrains the temperature conditions to between approximately 170 and 220°C, and an approximate maximum pressure of 7 to 9 kb, which corresponds to depths between 25 and 32 km (Fig. 48). Thus, the coherent sandstones and mélange matrix sandstones were metamorphosed at temperatures of approximately 170-220°C, and pressures of approximately 5-9 kb. This corresponds to a geothermal gradient of 4-13°C/km during subduction-related metamorphism.

Post-peak Metamorphism

Restoration of a normal geothermal gradient prior to depressurization would destroy the blueschist assemblages and possibly indicate a change in the subduction regime. The lack of a higher-temperature overprint and the presence of aragonite, which implies depressurization (or exhumation) below 175°C (Carlson and Rosenfeld, 1981), suggest that peak temperature conditions were attained during subduction.

Preservation of blueschist terranes in subduction complexes is accomplished by either rapid exhumation, or by prolonged exhumation during continuous subduction under steady-state refrigeration conditions (e.g., Sedlock, 1988). Cloos (1986) suggested that the near-perfect preservation of blueschist-facies minerals, lack of a high-temperature overprint, and the partial preservation of aragonite within the Franciscan

Complex suggest that its exhumation occurred over tens of millions of years during continuous subduction.

STRUCTURAL GEOLOGY

Temblor Sandstone

Temblor Sandstone beds consistently strike northeast to northwest and dip moderately west, as also recognized by Dibblee (1973) and Graymer et al. (1996). Christie (1985) mapped northwest-trending folds in late Cenozoic sediments across Alameda Creek to the north, and Dibblee mapped folds across Calaveras Creek to the west. Based on attitudes of the Temblor, these folds do not continue into my study area, but the Temblor Sandstone beds may be part of a fold with a wavelength larger than the outcrop area.

The contact between the Temblor Sandstone and the Franciscan Complex is not exposed but is probably a fault because Temblor beds strike into the contact (Plate 1, location 8). Dibblee (1973) and Graymer et al. (1996) also mapped Temblor Sandstone overlying Franciscan Complex rocks along a fault on the east side of the reservoir (Plate 1, B-1, B-2, C-1, C-2, D-2), and along an unconformity on the west side of Calaveras Creek in quarry and roadcut exposures.

Franciscan Complex

Few mesoscopic structural data are available for the Franciscan Complex in the study area. Fault surfaces are not exposed, and the rocks display no kinematic or geopedal indicators. Folds were observed in only one outcrop. Thus, most of the structural data described herein are based on map relations and thin section observations,

chiefly of the coherent sandstone units. The Calaveras Creek block, which probably was more strongly affected by late Cenozoic faulting than the rest of the field area, will be described separately.

Coherent Sandstone

Bedding and foliation within the coherent sandstones typically strike north to northwest and dip moderately east (Plate 1). These sandstones are mostly Textural Zone 1-2A, and original clastic texture is clearly visible in hand sample. At a few locations, strike and dip of foliation change significantly within a single outcrop (Plate 1, B-3, C-3). In general, bedding and foliation are subparallel, and fractures commonly have a spacing of about 3-6 cm in outcrop (Fig. 43). In thin section, foliation generally is parallel to and defined by aligned small shale chips and very fine-grained white mica. These observations suggest that if the sandstones are folded, the folds are probably west-vergent isoclinal folds.

Mélange

Information on mélange matrix is based on very few outcrops. In one location, bedding in mélange matrix strikes east-west, and dips steeply north. The shale matrix has pervasive anastomosing cleavage. Mélange matrix sandstone generally is less-deformed than the matrix shale, and generally has the same range of textural development as the coherent sandstone (Fig. 9). However, matrix sandstone is locally intensely sheared, and

shows the same type of anastomosing cleavage as the shale. Veins are locally folded and offset.

A *mélange* block-matrix contact is exposed in only one location where a lens-shaped conglomerate block is enclosed in sheared shale matrix (Plate 1, location 4; Fig. 13). Foliation in the block is more closely spaced toward its contact with the matrix, and wraps around the block. Individual conglomerate clasts within the block are more flattened nearer the contact (Fig. 49).

Microscopic Observations

Several thin sections were analyzed to better understand deformation in the coherent sandstones and *mélange* matrix sandstones. The two types of sandstones have about the same degree of recrystallization and textural development, but the matrix sandstones generally show weaker development of blueschist-facies minerals. However, I was able to analyze very few samples from the *mélange* matrix, so the slight difference could be an artifact of sampling.

TZ 1-2A samples contain moderate matrix development relative to TZ 2A, and widespread embayments, but lack significant development of foliation and syntaxial overgrowths (Fig. 7). Grain boundaries are defined by isotropic phases, and grains show a vague preferred orientation. TZ 2A samples have a distinct fabric defined by flattened grains, isotropic insoluble phases, and aligned white mica (Figs. 44, 50, 51). TZ 2A samples show widespread embayments, and some syntaxial overgrowths (Figs. 50 and 51). Most mica grains, especially those that are obviously metamorphic, are aligned in

Figure 49. Sheared mélangé block-matrix contact. Same block as in Figure 13. A discrete shear surface is visible (dashed line), but the block becomes progressively deformed toward the contact. Also note that foliation wraps around the block. Pencil for scale.

Figure 50. Photomicrograph showing deformation in a TZ 2A coherent sandstone. Note the syntaxial overgrowths, embayments, flattened grains, and undeformed larger grains. Plane-polarized light. Base of photo 3.3 mm.

Figure 51. Photomicrograph showing deformation in a TZ 2A coherent sandstone. Same view as Figure 50. Most, but not all, quartz grains show syntaxial overgrowths and embayments. Most quartz lacks subgrains. These observations suggest that not only are these rocks weakly recrystallized, but also they have not been subjected to temperatures high enough for quartz to undergo dislocation processes (see text). Crossed polars. Base of photo 3.3 mm.

the foliation. Some micas are bent or squeezed between grains, and some cut across grain boundaries. Micas oriented oblique to the structural grain are commonly bent or broken. Deformation mechanisms in these rocks are discussed in the last chapter of this report.

Coherent Sandstone-Mélange Contacts

Contacts between coherent sandstones and *mélange* probably are bedding-parallel faults. Although the contacts are not exposed, they can be mapped with relative precision (see above) and apparently are sharp. Bedding and foliation attitudes from coherent sandstone typically are subparallel to contacts with *mélange*, except in a few places where contact have been modified by high-angle faulting. Bedding-parallel faults, and faults separating coherent and *mélange* units, have been widely interpreted in the Franciscan Complex in areas that also have poor exposure. It is possible for landslide complexes to complicate interpretation of bedrock relationships, but the only place in the study area that this likely is in grid areas 2-C and 2-D on Plate 1.

The timing of juxtaposition of coherent sediments and *mélange* has been shown to be post-metamorphic in the Diablo Range and northern Coast Ranges, based on age data and juxtaposition of contrasting metamorphic grades (e.g., Cowan, 1974; Worrall, 1981; Blake and Wentworth, 1999). The faulting regionally involves the Late Cretaceous Burnt Hills terrane, so it must have occurred sometime after deposition and metamorphism of that terrane.

In the study area, timing of the faulting between coherent sandstone and *mélange* is unclear because age data are absent. However, coherent sandstones have slightly higher textural grades and more strongly-developed blueschist-facies assemblages than *mélange* matrix sandstones, which may indicate that the two units had different metamorphic histories and were juxtaposed following metamorphism.

Calaveras Creek Block

The Calaveras Creek block is mapped as one structural group of rocks that consists of several slivers of chert, sandstone, metatuff, greenstone, and *mélange* (Plate 1, A-1, A-2, B-1, and B-2). Structural slivers in this area appear to be in high-angle contact, and are very closely spaced relative to the rest of the area where the structure is more homogenous. Field relations suggest that the slivers probably are not individual *mélange* blocks, but instead comprise a fault-bounded group of rocks from either a separate coherent terrane or from a different part of the terrane that occupies the rest of the study area.

Chert and sandstone described earlier (Plate 1, location 5) are strongly deformed. The chert is disharmonically folded and the sandstone has well-developed foliation and isoclinally folded veins (Figs. 20-22). Where exposed, some of the sandstone beds in the area are parallel to foliation (Fig. 47). The contacts between the chert and sandstone are gently folded, and truncated by minor faults that are oblique to bedding (Fig. 20). Further measurements of fold and fault geometry were not made.

The upper part of the section is chert and the lower is sandstone, so if the contacts are depositional, I suggest that the section is probably overturned because in a sequence of dominantly continental margin deposits such as this, one would expect any significant amount of chert to be stratigraphically lower. Possible depositional environments of these rocks are discussed in the last chapter of this report.

Deformation was analyzed in sandstone exposed in the Calaveras Creek block along Alameda Creek (near location 5 on Plate 1). The sandstones are TZ 2B, but lack evidence of crystal-plastic deformation. The TZ 2B sandstones are texturally similar to coherent sandstones, but show more extensive development of the following textures: jadeite replacement, syntaxial overgrowths on quartz grains, flattened grains, embayments in quartz, polycrystalline quartz produced during jadeite formation, white mica growth, and extensive destruction of clastic texture (Fig. 39). Foliation development in these rocks has strongly modified the primary crystal habit of jadeite (Fig. 38), and some jadeite is mantled by insoluble phases similar to those in the matrix of coherent sandstones (Fig. 52). Despite the higher degree of deformation in sandstones of the Calaveras Creek block, they share common deformation features with the coherent sandstones. Deformation mechanisms are discussed in the last chapter of this report.

Relative Ages of Faulting

Rocks in the study area have undergone at least four generations of faulting. The first phase placed the coherent sandstone and *mélange* units in contact along a low-angle fault. Cross-sectional views and map patterns of coherent sandstone suggest that the

Figure 52. Photomicrograph showing deformation in a TZ 2B sandstone. This rock has jadeite (arrow) mantled by insoluble phases. Plane-polarized light. Base of photo 1.32 mm.

sandstone was once a sheet-like, fault-bounded body (Plate 1, B-2, B-3, C-4, and C-5). Others have also recognized this type of structure in Diablo Range Franciscan rocks (e.g., Cowan, 1974). In map view, the contact between the two units is curvilinear, and parallel to contours. The simplest way to interpret the structures is that the coherent sandstone overlies the *mélange*. Unfortunately, the ages of the rocks are unknown, and no kinematic indicators are available to determine whether this fault had a normal or reverse sense of slip.

A second phase of dip-slip faulting is recorded in the eastern part of the map area (Plate 1, B, C, and D-4). This phase truncated phase 1 low-angle faults, and may have a normal sense of slip based on projection of the original sandstone/*mélange* contact.

The third and fourth phases of faulting are most apparent in the western portion of the field area (Plate 1, A, B, C, and D-1, and A, B, C, and D-2), although one fault is evident in the central portion as well (Plate 1, B, C, and D-3, Fig. 11). These stages of faulting are strike-slip and thrust faulting most likely associated with the nearby Calaveras fault.

Phase 3 faulting emplaced Temblor Sandstone over Franciscan rocks along faults of variable, but generally not steep, dip as mapped by Graymer et al. (1996), Wentworth et al. (1999), and this study. The Temblor probably did not travel more than about 2 km because the basal contact with the Franciscan is depositional across Calaveras Creek to the west (Graymer et al., 1996). I suggest these faults may be part of a flower structure associated with earlier stages of Calaveras fault activity. Massive landsliding and

topographic benches may also be geomorphic evidence of other unmapped faults in this area.

The fourth and youngest phase of faulting is characterized by north-south-striking, high-angle faults, and is discussed further in the last chapter of this report because these faults are previously unmapped.

DISCUSSION

Blueschist Detritus: Constraints on Exhumation Rates

In this study I have identified rare evidence of blueschist detritus within Franciscan Complex sandstones (Figs. 27 and 28). The detrital grains are enclosed in sedimentary rocks with a probable of Tithonian (~ 147-145 Ma) depositional age (Elder and Miller, 1993). The source of the detritus must have been Franciscan blueschist exposed after the time of the blueschist overprint in the oldest high-grade blocks at about 162 Ma (Mattinson, 1986; Ross and Sharp, 1986) and the oldest coherent blueschist at about 146 Ma (McDowell et al., 1984) to 143 Ma (Wakabayashi and Deino, 1989). However, the accuracy of the metamorphic ages for the coherent terranes has been questioned by some (e.g., McDowell et al., 1984; Wakabayashi, 1992) who believe that the actual ages of those rocks are older than the data reflect. Nevertheless, the most likely source for this detritus is an old, high-grade coherent terrane such as the Skaggs Springs schist or similar rocks near Panoche Pass (about 100-130 km south of the study area), which contain neoblastic lawsonite/white mica intergrowths similar to those in this study (John Wakabayashi, written comm., 2002). Additionally, the jadeite grain (Fig. 28) displays a texture probably derived from a coherent terrane (John Wakabayashi, written comm., 2002).

The detrital lawsonite intergrown with white mica in Figure 27 is coarser-grained than lawsonite not associated with white mica. Both Brothers and Grapes (1989) and Crawford (1975) have also noted the increased grain size and higher birefringence in

lawsonite associated with white mica. They also presented geochemical data that distinguish both the lawsonites and white micas from the other, more common occurrences. Crawford suggested that the compositional differences might indicate temperatures of formation, which is probably consistent with conditions of metamorphism for older blueschist.

Published evidence for exhumation during the early stages of subduction is limited to high-grade Franciscan olistoliths in the basal Great Valley Group (e.g., Carlson, 1983). My study is the first to present evidence for early exhumation of coherent blueschist.

This finding also provides the opportunity to roughly estimate a minimum syn-subduction exhumation rate for large tracts of the oldest parts of the Franciscan. I cannot estimate a maximum exhumation rate because some metamorphic ages are younger than the sedimentary rocks in my study. However, based on the occurrence of detrital blueschist minerals in these rocks, blueschist must have been exhumed and exposed between about 147-145 Ma and 162 Ma. Using minimum exhumation rate based on the oldest metamorphic age and the youngest fossil age, and an estimated depth of metamorphism of 35 km, I estimate a minimum exhumation rate of 2.1 mm/yr.

QFL Comparisons

The similar detrital modes of coherent and mélange matrix sandstones suggest that, though these units have had different post-depositional tectonic histories, they may have once been part of the same sedimentary sequence. Such a relationship would have

significant implications for understanding the origins of both units and their tectonic histories.

The only other specific study of detrital modes of Franciscan *mélange* matrix sandstones, from the Central terrane of northern California (Jayko and Blake, 1984), reported much higher lithic content than what is found here (Fig. 53, field 5). Blake and Wentworth (1999) also noted similar composition between matrix sandstone in the Diablo Range and northern California, but presented no data. *Mélange* matrix sandstones in my study area are compositionally similar to sandstones in the Eylar Mountain and Yolla Bolly terranes (Fig. 53, fields 3 and 4). Although I point counted only 5 matrix sandstones, their compositional range varies no more than that of the coherent sandstones.

The coherent sandstone data from my study (Fig. 26) compare favorably with other data from the Diablo Range (e.g., Cowan, 1974; Crawford, 1975; Jacobson, 1978). These rocks plot within the compositional field of the Eylar Mountain terrane (Fig. 53, field 3), which has been correlated with the Late Jurassic to Early Cretaceous Yolla Bolly terrane (Fig. 53, field 4) of northern California based on composition, age, rock type, and metamorphic grade (Blake et al., 1982, 1984). According to Jayko and Blake (1984), the Yolla Bolly terrane also contains Cowan's Zimba metagraywacke and Garzas *mélange* (Fig. 53, field 2), and Jacobson's Eylar Mountain sequence and Las Aguilas Creek *mélange* near Panoche Pass. These units are apparently all the same age, but the purported correlation is not supported by all of the QFL data (Fig. 53).

Figure 53. QFL comparison diagram. Includes the data from Figure 26, and other published data. Outlined fields are copied directly from others, except (2) is modified from Jacobson (1978). Fields (1) and (3) from Jacobson (1978), field (2) from Cowan (1974), fields (4) and (5) from Jayko and Blake (1984). Abbreviation: ss—sandstone.

Figure 53 also shows that some *mélange* blocks and *mélange* matrix sandstones from the study area are compositionally similar to the Cretaceous Burnt Hills terrane (Fig. 53, field 1; Jacobson, 1978; Jayko and Blake, 1984), which crops out along the axis of the Diablo Range (Blake et al., 1984). The Burnt Hills terrane is younger than the Yolla Bolly and associated terranes (Jacobson, 1978; Jayko and Blake, 1984).

Roughly half of the sandstone *mélange* blocks I mapped are lithologically similar to the adjacent coherent sandstone, and more commonly in areas near a contact. Cowan (1974), Worrall (1981), and Wentworth et al. (1999) also noted this type of field relationship, and the observation is supported at least in part by detrital modes of sandstone *mélange* blocks from this study, Cowan (1974), and Jacobson (1978) (Fig. 53). This suggests that the protoliths for coherent sandstone, *mélange* matrix, and sandstone *mélange* blocks may have been the same sedimentary sequence.

Three problems limited my ability to answer important questions with petrography.

- 1) The high degree of alteration and metamorphic recrystallization, and the prohibitively small grain size in some samples, prevented me from obtaining accurate detrital data (see discussion in Methods section), and limited the number of thin sections that could be point-counted from the *mélange* block and *mélange* matrix units. Thus, I have insufficient data to determine conclusively whether the sandstone *mélange* blocks and/or *mélange* matrix sandstones share a common protolith with coherent sandstone.

- 2) Small, isolated outcrops of sandstone from *mélange* blocks, *mélange* matrix, and coherent units may have similar appearance in outcrop, and are not always

identifiable as part of a specific lithologic group based on field relationships (Fig. 9).

Worrall (1981) also noted this problem.

3) The compositional similarities among sandstones from the three affinities prohibit assignment of a given sample to one of the three units based solely on detrital mode. Thus, a number of samples of questionable lithologic affinity were not point-counted as originally planned.

In summary, coherent, *mélange* matrix, and *mélange* block sandstones in the study area have detrital modes that overlap each other significantly, and thus are practically indistinguishable on a QFL diagram. Though field relations and alteration/metamorphism have precluded a comprehensive analysis, the similar compositions found here suggest the possibility of a common protolith for these rocks. The distinction of *mélange* matrix sandstone composition in the study area from previously studied matrix in northern California suggests more than one protolith for Franciscan *mélanges*.

Late Cenozoic Strike-slip Faulting

The Calaveras fault is a major right-lateral strike-slip fault of the San Andreas fault system that probably has been active since about 12-13 Ma (Wakabayashi, 1999c). At least two traces of the Calaveras fault have been mapped just beyond the western edge of the study area (Graymer et al., 1996; Wentworth et al., 1999). Secondary faults associated with the Calaveras and nearby Hayward fault have also been identified nearby, west of my study area. My mapping of faulted Miocene Temblor Sandstone and

Franciscan Complex outcrops within the western portion of the study area suggests the presence of two other previously unmapped Calaveras-parallel faults.

Several maps show a fault-bounded body of Temblor Sandstone east of Calaveras Reservoir (e.g., Crittenden, 1951; Dibblee, 1973; Graymer et al., 1996; this study). Graymer et al. (1996) mapped a smaller fault-bounded body of Temblor near the east end of the Calaveras Reservoir dam (Plate 1, B-1). I identified a very small outcrop ($< 2 \text{ m}^2$) of Temblor within a saddle at the end of the east-west trending ridgeline near the intersection of Alameda and Calaveras Creeks (Plate 1, location 6, Fig. 19). A few meters west of this Temblor outcrop is a small outcrop of what appears to be vein quartz. Very limited exposures precluded mapping the extent of these outcrops in any direction. This Temblor outcrop, and the one mapped by Graymer to the south, line up well with the west end of the larger body of Temblor farther south. A roughly north-south-striking fault would appropriately connect the three outcrops, and be subparallel to mapped traces of the nearby Calaveras fault. The distribution of the two small Temblor outcrops suggests they have been offset in a right-lateral sense.

The Temblor Sandstone body in grid areas C-1 and C-2 on Plate 1 is in fault contact with the easternmost body of Temblor Sandstone, as shown by truncated contacts, and a truncated Claremont Chert section (Dibblee, 1973; Graymer et al., 1996). This second north-south-striking fault, if projected to the north, would coincide with a significant Franciscan lithologic and structural boundary. This proposed fault would also coincide with a ridgeline saddle and massive landslides.

Structural Relationship Across Alameda Creek

To better understand the structural relations within the study area, I have attempted to project my mapping north across Alameda Creek, where Christie (1985) produced a detailed map. Comparisons are based on thorough review of Christie (1985), and my limited reconnaissance work in his study area.

The area mapped by Christie contains units that are distinctly different from those in my map area, such as abundant large Franciscan Complex chert, greenstone, and serpentinite bodies, Coast Range Ophiolite serpentinite, an outlier of the Great Valley Group, and an extensive late Cenozoic section. Christie mapped most of the Franciscan as *mélange* with large inclusions of sandstone, chert, and greenstone, and called two of the larger blocks semi-coherent units. In contrast, the majority of my field area is characterized by extensive tracts of coherent Franciscan sandstone in fault contact with *mélange*, and typically much smaller *mélange* blocks. Many Franciscan sandstones in the two study areas are similar, but those in Christie's study area seem more texturally reconstituted. Franciscan chert in the two areas is similar, but in Christie's area it is more abundant and appears to be closely associated with sandstone and greenstone. The Calaveras Creek block of my study area has no correlative unit in Christie's area, even though the two areas abut.

The differences between Franciscan Complex rocks in the two areas may be the result of an intra-Franciscan discontinuity, more recent deformation, or some combination of the two. Along-strike variations are characteristic of the Franciscan (Wakabayashi, 1992, 1999a,b). Therefore, an east-west-trending Mesozoic fold or fault

within the Franciscan, similar to what others have mapped in the Diablo Range (e.g., Raymond, 1973; Ernst, 1993) and near San Francisco (e.g., Warhaftig, 1984; Wakabayashi, 1992), could account for the differences between the adjacent areas. Another possibility is that the rocks mapped by Christie are part of a broken formation unit similar in lithology to rocks in my study area. Mélange mapped by Christie contains only trace amounts of exotic blocks. Ernst (1993) near Pacheco Pass, and Worrall (1981) in northern California mapped correlative Franciscan rocks of the Yolla Bolly terrane and concluded that areas of broken formation are associated with coherent sandstone and mélange terranes. This scenario may not require a discrete discontinuity, but possibly a zone of shearing that marks a transition from south to north. Finally, Cenozoic tectonism may have complicated Mesozoic structures in this area. Christie mapped several northwest-trending folds and high-angle faults that affected the Franciscan rocks in his study area. However, I do not see evidence for the same faults in my study area, and the attitudes I measured are not consistent with what one would expect based on the folds Christie mapped to the north.

Based on the above discussion, I interpret the boundary between the two areas to be an east-west-trending Mesozoic fault contact, which may have been modified by later folding and possible faulting.

Deformation Mechanisms

Widespread syntaxial overgrowths, embayments, flattened grains, and lack of evidence for significant crystal-plastic deformation indicate that pressure solution was the

dominant deformation mechanism in these rocks (Fig. 51). Mechanical rotation of micas also occurred. Aragonite in veins indicates that pressure solution and formation of veins may have been synmetamorphic. Deformed jadeite (Fig. 38) and bent or internally deformed micas suggest that deformation continued after the peak of metamorphism. Preservation of the blueschist-facies assemblage and lack of significant quartz dislocation indicates that temperatures did not increase significantly during deformation. The symmetric growth tails and general lack of kinematic indicators imply the rocks were deformed by pure shear. These conclusions are similar to those of Ring and Brandon (1999), who interpreted deformation mechanisms of Franciscan sandstones. Their work suggests that pressure solution is the dominant deformation mechanism in the lower accretionary wedge.

Interbedded Chert and Sandstone

Interbedding of chert and sandstone, observed in the study area as well as in other parts of the Franciscan, requires special depositional processes and environments. For example, chert in the Marin Headlands terrane accumulated at rates of about 0.3 mm/ka to 2.5 mm/ka (Murchey and Jones, 1984; Hagstrum and Murchey, 1993). In contrast, turbidites on the modern Madeira Abyssal Plain can accumulate at rates of about 1.7-250 mm/ka (Stow et al., 1996). Even the fastest rate of chert sedimentation would require 60 ka to produce the 15-cm-thick chert bed described in the study area. It is highly unlikely that so much time passed between turbidity currents in the thickly sedimented Franciscan subduction zone. Thus, the interbedding probably occurred at the most distal edge of a

fan near the abyssal plain, in a high-productivity zone such as a marginal basin, or due to pelagic turbidity currents generated by instability upon a bathymetric high.

Christie (1985) noted what he interpreted to be interbedded chert and sandstone north of Alameda Creek, adjacent to my study area. However, during reconnaissance in that area, I did not find rocks correlative to those exposed in Alameda Creek.

The gradational contacts observed in outcrop (Figs. 21 and 22) confirm that the chert layers are primary sedimentary features. Unfortunately, the small outcrop size prohibited determination of a specific depositional environment. Nevertheless, the interbedding clearly exposed in this rare outcrop contrasts with rocks studied by Isozaki and Blake (1994), who identified repeated sequences of thin fault slices of chert, and fault contacts between chert and sandstone or mudstone.

CONCLUSION

This study of Franciscan Complex rocks has produced new lithologic, petrologic, and structural data from an area that had not been previously described in detail. Based on these data, the following interpretive subjects are addressed. 1) Detrital blueschist minerals with Franciscan sandstones imply that large-scale exhumation occurred earlier than had been previously documented, and suggests a minimum estimated exhumation rate of 2.1 mm/yr. 2) Point counts of sandstones in my field area suggest that coherent, *mélange* block, and *mélange* matrix sandstone share a common protolith. Those data also show that *mélange* matrix in the Diablo Range is lithologically distinct from Central terrane matrix in northern California, implying separate *mélange* protoliths. 3) An outcrop of Temblor Sandstone in the Calaveras Creek block, coupled with previously mapped outcrops, and an abrupt change in Franciscan lithology suggest the presence of a previously unmapped late Cenozoic fault zone probably related to the Calaveras fault. 4) The boundary between Franciscan Complex rocks in this study area and those directly to the north is probably an east-west-trending Mesozoic fault similar to other such faults in the Franciscan. 5) Analysis of deformation mechanisms in sandstones show that pressure solution was the dominant deformation mechanism in coherent and *mélange* matrix sandstones. 6) Gradational contacts between Franciscan chert and sandstone indicate that not all contacts between such units are faulted.

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#	Q	F	L	Qp	Qm	Plag	K-spar	Chert	Lv	Ls	Lm	Mica	Mineral	Matrix	Other	Total
92b	29	45	26	22	95	184			68	1	28	10		101	5	514
98b	30	56	14	20	91	211			24		16	12		88	5	467
96b	30	44	26	15	113	193			61	3	41	8		64	6	504
88b	25	62	13	32	83	287		4	29		23	3	2	59	4	526
89b	29	48	23	37	106	234			77		31	5	1	3	1	495
36	22	51	27	10	81	209			90	4	14	4		59	3	474
34	26	52	22	27	99	247			88	3	11	2		39	2	518
40	27	49	24	35	103	246			91	4	17	10		12	1	519
	27	51	22	25	96	226			66		23					
67	20	45	35	13	80	214			105	23	32	6	1	5	6	485
117	24	53	23	25	80	226		1	78	7	11	1		10	3	442
118	28	58	14	11	114	263		2	46	1	7	5		21	5	475
32	25	29	46	14	97	124			103	9	84	1	1	21	8	462
	24	46	30	16	93	207			83		34					
113	36	50	14	63	105	230			48	1	12	3	1	11	5	479
115	30	39	31	11	141	199			116	11	21	5	1	2		507
72	30	46	24	3	121	191		1	68		21	7	1	12	1	426
50	30	61	9	4	116	250			31		3	3	1	33	10	451
51	32	58	10	9	133	253			34		5	3	2	35	9	483
	32	51	17	18	123	225			59		12					
	28	49	23													457

Appendix. Raw QFL data. Q, F, and L are normalized. Qp—polycrystalline quartz, Qm—monocrystalline quartz, Lv—volcanic rock fragments, Ls—sedimentary rock fragments, Lm—metamorphic rock fragments. Sample numbers 92b-40 are coherent sandstones, 67-32 are sandstone mélange blocks, and 115-51 are mélange matrix sandstones. Bold numbers are averages.

NOTE TO USERS

Oversize maps and charts are microfilmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

This reproduction is the best copy available.

UMI[®]

SYMBOL

Symbols for melange bl

- sandston
- greensto
- chert
- ◆ blueschis
- conglome
- ❖ amphiboli
- ⊠ greenstor
- ◇ plutonic

Strike and dip of bedding

- ²⁷ Inclined
- Vertical

Strike and dip of foliation

SYMBOLS

Symbols for melange blocks less than 30 m

- sandstone
- greenstone
- chert
- ◆ blueschist
- conglomerate
- ❖ amphibolite
- ▣ greenstone/chert
- ◇ plutonic

Strike and dip of bedding

27 Inclined

Vertical

Strike and dip of foliation in coherent
sandstone unit

GEOLOGIC MAP a
from th
CALAVER

ALAMEDA AND SANT

San Jo

37°30'

DES

MAP and STRUCTURE SECTIONS
from the area east of
VERAS RESERVOIR

AND SANTA CLARA COUNTIES, CALIFORNIA

By Ron S. Rubin
San Jose State University, 2002

DESCRIPTION OF MAP UNITS

JRE SECTIONS
of

RVOIR

S, CALIFORNIA

Incline

Vertical

Strike and dip of folial
sandstone un

78 Incline

Line symbols: dashed
short-dashed
queried where

Contact

Fault

Late Cenoz

Contact con
and

Fault compil
and

A - A' Location

3 Location

SCALE 1:

.1 0.5 0

inclined
Vertical

Strike and dip of foliation in coherent
sandstone unit

78
Inclined

Line symbols: dashed where approximated,
short-dashed where inferred,
queried where uncertain

-----?-----
Contact

-----?-----
Fault

Late Cenozoic fault mapped in this study

Contact compiled from Graymer et al. (1996),
and/or Wentworth et al. (1999)

Fault compiled from Graymer et al. (1996),
and/or Wentworth et al. (1999)

A - A' Location of cross-section

3 Location mentioned in text

★
MAGNETIC
NORTH
16.5° declination,
1980

SCALE 1:12 000

0

1 MILE

37°30'

B

C

D

37°29'

CALAVERAS FAULT

BM 779

Serpentine

Franciscan
Melange

933

MILE

37°30'

B

C

D

37°29'

B

lower to middle
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DESCRIPTION OF MAP UNITS

Claremont Chert

Buff to light gray, laminated siliceous mudstone.

Temblor Sandstone

Light yellowish brown, well-bedded to massive, fine- to medium-grained arkosic sandstone. Local conglomerate beds and distinctive coquina beds with abundant brachiopod shell fragments.

Franciscan Complex Coherent Sandstone

Chiefly massive sandstone with minor siltstone and shale interbeds. Sandstone is light green to light brown, fine- to medium-grained, with shale chips and mica that are parallel to bedding and foliation when present. There are rare pebble conglomerates, and occasional very fine-grained sandstone interbeds. Sandstone is mostly TZ 1-2A, and has locally well-developed planar foliation. Evidence of recrystallization in hand sample is minimal, but thin sections show abundant lawsonite, with rarer jadeite and aragonite.

Franciscan Complex Melange

Mixture of blocks of sandstone (ss), greenstone (gs), chert (ch), blueschist (bs), plutonic (pl), amphibolite, and conglomerate (cgl), which are contained in a rarely exposed dark gray to black shale matrix that has a pervasive scaly cleavage, and lesser amounts of sandstone interbeds. Matrix sandstone beds, where observed, are laminated, fine-grained, and generally TZ 1. Thin sections of matrix sandstone contain rare lawsonite.

Franciscan Complex Chert

Light green chert, with beds between 0.5 and 3 cm thick, and green shale interbeds that usually are less than 0.5 cm thick. Also contains white quartz veins up to 1 cm thick and is locally folded. Green and light blue meta-tuff unit along west contact.

Franciscan Complex Calaveras Creek block

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e pebble
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exposed
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SCALE 1:1

CONTOUR INTERVAL

Base map taken from parts of the La Costa Valley and ()
quadrangles, 1996 and 198

Some late Cenozoic geology in southwest
Graymer et al. (1996) and W

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Northwest

Bend in Section

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3

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B
West

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JKfccb

Francisca

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B'
East

Map of sample location

Also contains white quartz veins up to 1 cm thick and is locally folded. Green and light blue meta-tuff unit along west contact.

Franciscan Complex Calaveras Creek block

Slivers of meta-basalt, greenstone, sandstone, melange, and chert. Two types of chert are present: JKCh, and a highly deformed and recrystallized chert that is interbedded with highly recrystallized TZ 2B sandstone. Field relations are unclear because of generally poor exposures and limited accessibility.

sample locations from the study area. Abbreviations of geologic units are from above.

and is locally
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gic units are from above.

A
Northwest

Bend in Secion

A'
Southeast

B

West

37°29'

B'
East

Map of sample locations

Map of sample locations from the study area. Abbreviations of geologic units are from above.

ologic units are from above.

Plate 1