Kinematics of Franciscan Complex exhumation: New insights from the geology of Mount Diablo, California

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ABSTRACT

Three major lithotectonic units of an ancient arc-trench system are present in western California. In ascending structural order, they include: the Franciscan Complex, a remnant accretionary prism partly including high-pressure (blueschist-facies) metamorphic rocks in a subduction mélange; the relatively unmetamorphosed Coast Range ophiolite; and the Great Valley Group forearc sediments. In the Mount Diablo study area east of San Francisco, the subduction complex and ophiolite are juxtaposed across the Coast Range fault, and together they represent a structurally attenuated section through the ancestral forearc crust exposed by uplift and folding of the late Cenozoic Mount Diablo anticline. The Coast Range fault is locally associated with a sheared zone in the lower part of the attenuated ophiolite. Shear-sense indicators in the serpentinite, such as S-C fabrics, rotated clasts, and slickenfibers, record the deformation kinematics and consistently indicate that the ophiolite moved down in a normal sense relative to the Franciscan rocks in the modern reference frame. Based on these kinematic relations and metamorphic facies contrasts between the Franciscan and the Coast Range Ophiolite, as much as 6–18 km structural attenuation has occurred along the Coast Range fault. After restoration of vertical axis rotation and late Cenozoic fold deformation, the Coast Range fault dips at a low angle toward the northeast, and shear-sense data restore to top-to-the-northeast motion on the Coast Range fault, implying normal displacement of the ophiolite with respect to the structurally underlying Franciscan Complex. These relations are consistent with the hypothesis that the Franciscan rocks were exhumed by crustal attenuation along a low-angle fault system. These data suggest that the Coast Range fault dominantly accommodated normal displacement and ductile thinning, and that these processes were primarily responsible for the structural exhumation of high-pressure assemblages in the Franciscan Complex relative to the structurally overlying forearc crust.

Keywords: Franciscan Complex, exhumation, serpentinite, blueschist, forearc tectonics, crustal attenuation.

INTRODUCTION

The Franciscan Complex in western California is a classic example of a relict accretionary complex along a convergent margin where material has been subducted to depths of high-pressure metamorphism conditions and subsequently exhumed. This convergent setting was the first to be identified as an ancient subduction zone (Ernst, 1970). Subsequent studies have led to such fundamental concepts as wedge mechanics (Elliott, 1976; Davis et al., 1983; Dahlen et al., 1984; Platt, 1986), formation of tectonic mélanges in the subduction channel (e.g., Cloos, 1982; 1984; Cloos and Shreve, 1988a, 1988b), and exhumation mechanisms of deeply buried high P/T rocks (e.g., Platt, 1986).

Knowledge of the kinematics of faults juxtaposing rocks with contrasting metamorphic grade is crucial for assessing mechanisms of exhumation. To date, several mechanisms have been proposed to account for the exposure of high pressure/temperature (P/T) Franciscan rocks:

(1) Erosional exhumation, a two-step process that includes structural burial of high P/T rocks by overthrusting and subsequent removal of the overburden by erosion (e.g., Cowan et al., 1989; Ring and Brandon, 1994);
(2) Oblique-normal strike-slip motion within the trench and forearc region (e.g., Wallis, 1995; Mann and Gordon, 1996);
(3) Attenuation processes, whereby distributed extension in the lower crust is linked to normal faults in the upper crust. This process can account for exhumation of high P/T rocks but does not explain the commonly observed presence of lower pressure rocks structurally beneath the high P/T rocks (Platt, 1986; Jayko et al., 1987; Harms et al., 1992);
(4) Cross-sectional extrusion, a process that can account for the presence of lower pressure (P) rocks structurally above and below the high P/T rocks (Maruyama et al., 1996; Wakabayashi, 1999); and
(5) Buoyancy-driven processes that enable deeply subducted crustal rocks at structural levels of the upper mantle to rise until they are in pressure equilibrium (Ernst, 1970; Carlson, 1981). If high P/T rocks are blocks in a mélange, then return flow within the subduction channel can facilitate their exhumation (Cowan and Silling, 1978; Cloos, 1982; Pavlis and Bruhn, 1983).

Numerous authors have addressed the question of exhumation processes of high P/T rocks in the Franciscan Complex (e.g., Ernst, 1970; Cloos, 1986; Jayko et al., 1986, 1987; Blake et al., 1988; Dumitru, 1989; Ernst, 1993;

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Wakabayashi and Unruh, 1995; Moores et al., 2002), and the kinematics of the so-called Coast Range fault (Irwin, 1964; Bailey et al., 1970). The latter is the structural contact between blueschist-facies rocks in the Franciscan Complex and overlying greenschist (or lower)-facies rocks of the ancestral forearc crust. Conflicting interpretations of the Coast Range fault have arisen from analysis of kinematic shear-sense data. For example, Jayko et al. (1987) and Harms et al. (1992), working in the Diablo Range (Del Puerto Canyon, Fig. 1), interpreted the Coast Range fault as an extensional structure responsible for the exhumation of the high P/T rocks, whereas Ring and Richter (2004) subsequently concluded that no extensional structures exist in this area. In contrast, Ring and Brandon (1994, 1997), working within the Yolla Bolly terrane (Fig. 1), interpreted displacement on the Coast Range fault to be thrust/reverse and considered large-scale erosion to be responsible for rock uplift and exhumation of high P/T rocks, with minor contribution of solution mass transfer and ductile thinning (Ring and Brandon, 1999; Bolhar and Ring, 2001; Ring and Richter, 2004).

The key observation that these models address is the fact that a large section of crust is missing across the Coast Range fault. The ophiolite is only metamorphosed to greenschist facies (e.g., Williams, 1983a, 1983b, 1984; Platt, 1986; Springer et al., 1992), whereas coherent Franciscan rocks are commonly blueschist facies. The structural juxtaposition of lower P material on high-pressure rocks requires net attenuation across the fault. To date, the only kinematic mechanisms that can account for this are extension (e.g., Platt, 1986; Jayko et al., 1987; Harms et al., 1992) or out-of-sequence thrusting (e.g., Cowan et al., 1989; Ring and Brandon, 1999).

The Mount Diablo area, ~50 km east of San Francisco, California, lies between the study areas cited above and provides unique three-dimensional exposures of the structural contact between the Franciscan Complex and the Coast Range ophiolite. This paper presents a detailed analysis of local exposures of the Coast Range fault at Mount Diablo, focusing on the petrography of involved lithologies in relation to structures, the degree of metamorphism, and deformation kinematics. Based on these observations, we reconstruct the tectonic history of Mount Diablo and interpret the role of the Coast Range fault in the exhumation of the Franciscan Complex.

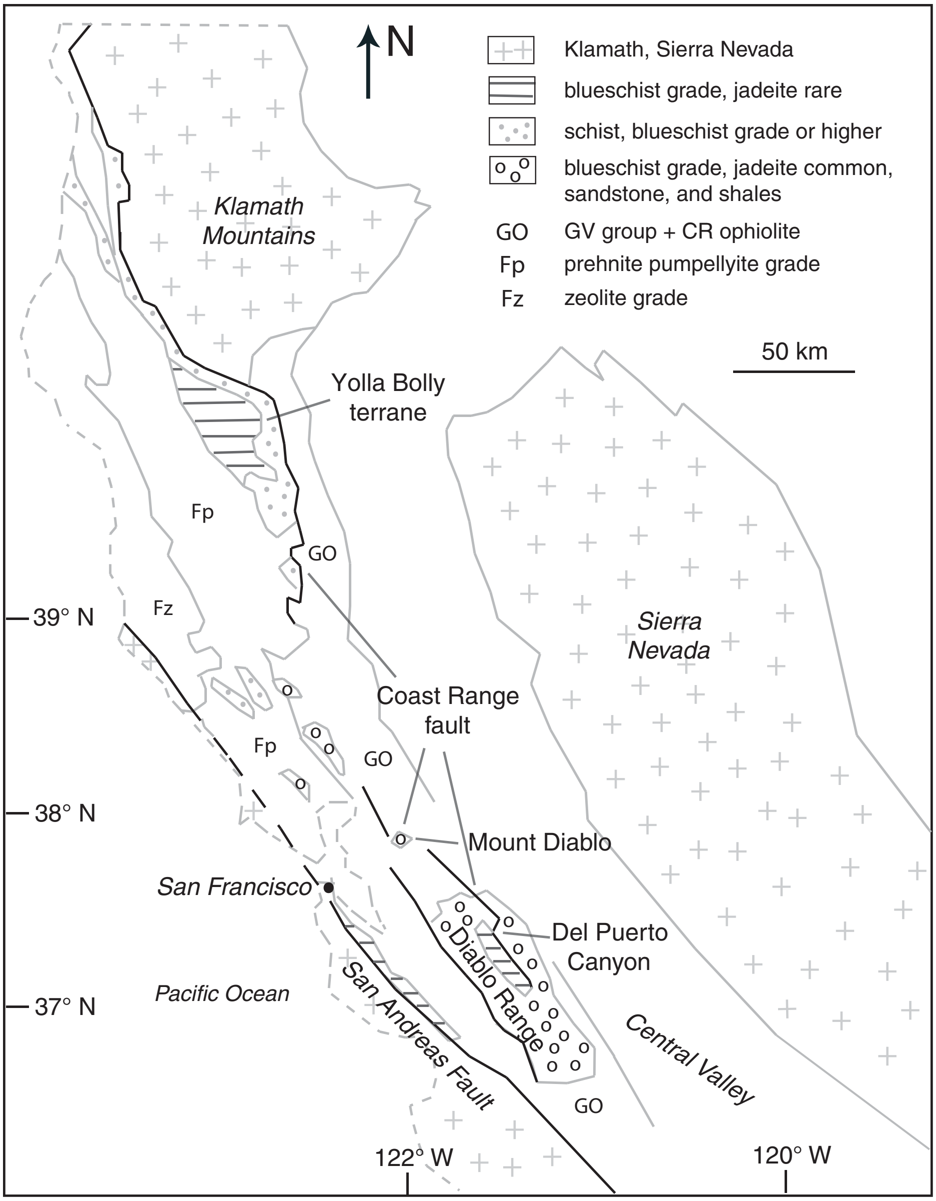

Figure 1. Simplified geological setting of northern California (after Wakabayashi, 1999). Kinematic studies of the Coast Range fault have been carried out within the areas of the Yolla Bolly terrane, Del Puerto Canyon, and Mount Diablo (this study). Metamorphic degree of Franciscan rocks and structural level increases toward the east up to the blueschist facies.

GEOLOGICAL SETTING

East-dipping subduction was active beneath central California from late Jurassic through late Neogene time (Atwater, 1970; Page and Engebretson, 1984). At the latitude of Mount Diablo, the convergent margin changed into a strike-slip margin after the passage of the Mendocino triple junction at ca. 10 Ma (Atwater, 1970). The Coast Range ophiolite, whose origin is still under debate (possibly representing part of an old backarc basin, a mid-ocean ridge, a forearc or intraarc basin, or an open-ocean setting [Hopson and Pessagno, 2005]; summary, e.g., by Dickinson et al., 1996; Shervais et al., 2005), was emplaced within the ancestral forearc region (Moores, 1970) and subsequently overlain by forearc basin deposits of the Mesozoic Great Valley Group (Blake et al., 1984).

The ophiolite experienced metamorphic pressures and temperatures no greater than those corresponding to the greenschist facies (e.g., Platt, 1986; Springer et al., 1992), probably owing to hydrothermal metamorphism during spreading rather than to burial metamorphism (e.g., Williams, 1983a).

The structurally underlying Franciscan Complex represents the remnants of an accretionary complex. The structurally highest Franciscan rocks directly beneath the ophiolite are blueschist facies and higher, implying subduction to depths of 10–30 km, depending whether the Franciscan forms coherent units or blocks in a mélange. The Franciscan rocks decrease both in structural level and metamorphic degree to the west (i.e., subduction to depths of <15 km; Bailey et al., 1964; Berkland et al., 1972; Suppe, 1973; Cloos, 1983, 1986; Jayko et al., 1986; Blake et al., 1988; Ernst, 1993).

Some of the Franciscan rocks form a tectonic mélange characterized by blocks of diverse composition, including greenstone, chert, shale, metasediment, and blueschist (e.g., Page and Engebretson, 1984; Blake et al., 1984, 1988; Ernst, 1993). More coherent blueschist units are typically found near the eastern margin of Franciscan exposure. They comprise nappes or fault-bounded units, intercalated with each other, or with mélange zones (e.g., Maddock, 1964; Raymond, 1970, 1973a; Cotton, 1972; Cowan, 1974; Crawford, 1975; Blake et al., 1981; Worrall, 1981; Blake et al., 1967).

At Mount Diablo, the Franciscan Complex, ophiolite, and forearc basin strata are exposed in fault contact with each other (Figs. 1 and 2). The study area discussed in this paper is ~18 km^2 and includes the structural contact (i.e., Coast Range fault) between the Franciscan and the ophiolite. The fault is marked by a coherent band of pervasively sheared serpentinite and other ultramafic rocks that probably are remnants of ophiolitic mantle. At present, the serpentinite band strikes NE-SW, extends for ~7 km, and ranges in width from ~1 km in the southwest to ~400 m in the northeast (Fig. 3). The Coast Range ophiolite crops out northwest of the contact, and Franciscan rocks crop out to the southeast (Figs. 3 and 4). These map-scale relations indicate that the study area comprises an oblique, northwest-dipping section through parts of the ancestral forearc crust.

Zircon and apatite fission-track data indicate that high-pressure Franciscan rocks regionally rose from depths of ~30 km to 10 km from 100 to 70 Ma and continued to rise relative to the Earth's surface until the mid Tertiary (Dumitru, 1989; Tagami and Dumitru, 1996). Since ca. 4 Ma, Mount Diablo has grown to its present elevation (about one km above sea level) as an asymmetric, southwest-vergent fault-propagation fold (Unruh et al., 2007). The anticline lies in a restraining stepover between the dextral Greenville and Concord faults (Unruh and Sawyer, 1995), both of which are strike-slip faults of the San Andreas system (Fig. 2). The northeast limb of Mount Diablo anticline exposes Mesozoic Great Valley Group strata and younger marine forearc

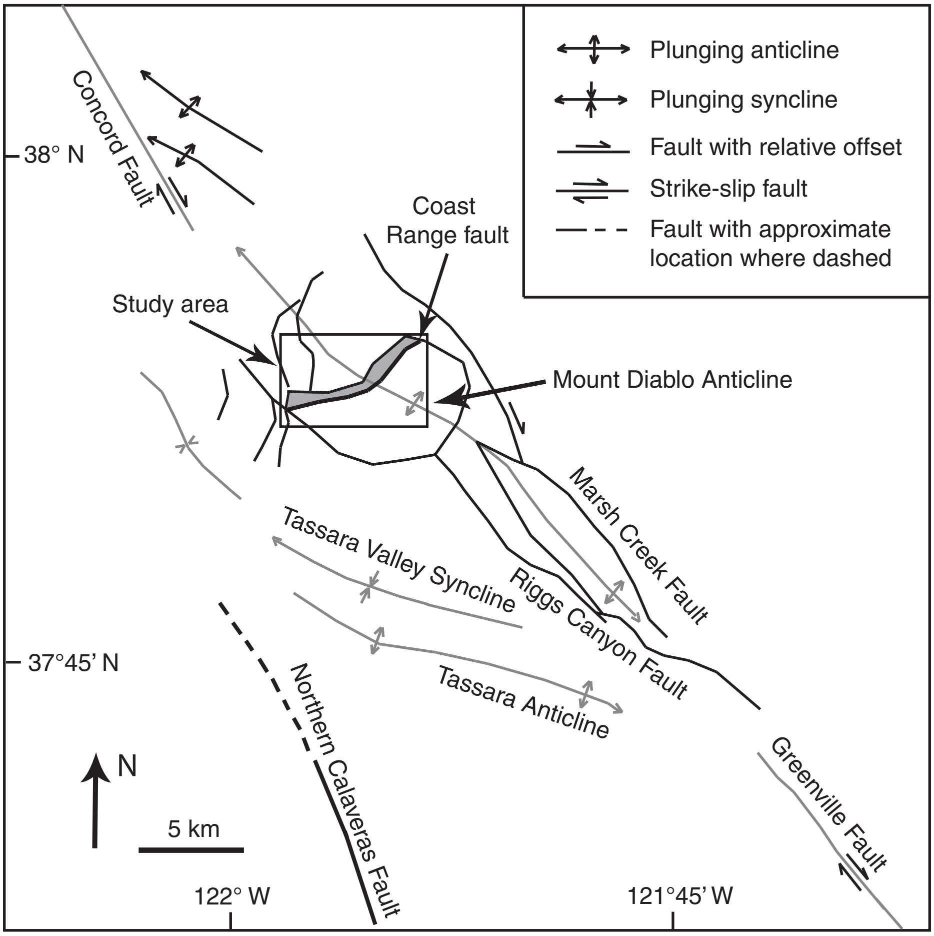

Figure 2. Structure map of the Mount Diablo region: several northwest-southeast–striking anticlines and synclines comprise a late Cenozoic fold-and-thrust belt (e.g., Mount Diablo anticline, and Tassajara anticline). The Greenville Fault and the Concord Fault are two dextral strike-slip faults associated with late Cenozoic transpressional tectonics. These still-active structures are colored gray. The box indicates the location of the study area, in which the serpentinite band is colored dark gray. It marks the fault zone of the Coast Range fault, which is the structural contact between the Coast Range ophiolite and the Franciscan Complex.

deposits; the SW limb comprises late Neogene continental fluvial deposits (e.g., Colburn, 1961; Dibblee, 1980; R.C. Crane, 1988 and 1995, unpublished map; Crane, 1995). The core of the anticline includes Franciscan rocks and the ophiolite. Folding of these rocks about the axis of the anticline provides unique 3-D exposures of the first-order structural relations (Unruh et al., 2007).

The late Cenozoic growth of Mount Diablo is related to the modern transpressional tectonic regime in western California, which has deformed older structures and structural relations that originally developed during subduction. Based on analysis of paleomagnetic data and map-scale geologic relations, Williams (1983a) argued that a total of ~100° of counterclockwise rotation about a vertical axis has occurred in the Mount Diablo region, ~30° of which occurred during late Cenozoic time.

METHODS

Over sixty thin sections for petrographic analysis were prepared from samples of outcrops located within the shear zones associated with the Coast Range fault, and many proved useful for kinematic analysis. Oriented samples were collected in the field and later cut perpendicular to the XZ plane of finite strain. Macroscopic kinematic indicators include serpentinite slickenlines and slickenfibers as well as S-C fabrics. We used slickenfiber data from one outcrop of the shear zone at Murchio Gap (Fig. 3) for fault-slip analysis with the algorithm FLTSLP (R.J. Twiss and L. Guenther, University of California,

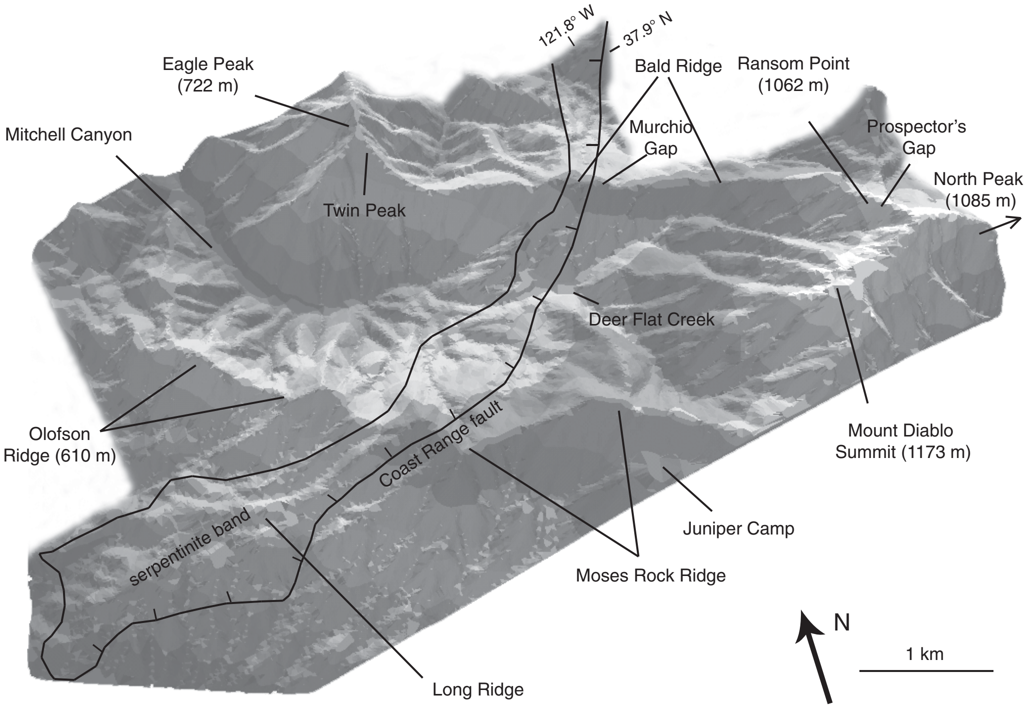

Figure 3. Topography of the study area with main morphological features and Coast Range fault. The serpentinite band separates the ophiolite from the Franciscan units. Each change of shading indicates a contour interval of 200 feet.

Davis), which finds a best-fit reduced strain rate tensor for populations of fault-slip (i.e., kinematic) data (Twiss and Unruh, 1998). This analysis is discussed in greater detail below.

We first present new petrographical and structural observations that are important for interpreting kinematics, describe crosscutting relations, and then discuss the results of kinematic analyses of shear-sense indicators. Finally, we restore deformation associated with late Cenozoic growth of Mount Diablo anticline, to interpret the kinematics of the Coast Range fault in the context of a Late Cretaceous–early Tertiary reference frame, coeval with exhumation of the Franciscan rocks during plate convergence and subduction.

FRANCISCAN COMPLEX

The Franciscan Complex forms a coherent unit at least 6 km in length, 2 km in width, and ~500 m in structural thickness with most prominent exposures at high-relief areas around Mount Diablo Peak and North Peak. Lithologies include fault-bounded units of metasediments (metagraywacke and sandstone), chert, and rare greenstone. Mélange zones containing small blocks in a pelitic matrix are limited to a few outcrops, which have dimensions less than 20 m in length, 3 m in width, and 3 m in height. Generally, exposures of blocks can be found in the low-relief areas and have probably been translated by erosion from coherent units above.

Metasediments

Franciscan sandstones are predominantly medium- to coarse-grained with minor fine-grained layers. They contain dominant quartz and plagioclase, subordinate lawsonite and jadeite, and accessory white mica. The only primary structure recognized is transposed bedding. The northwest dipping schistosity is the dominant foliation that becomes more penetrative near the shear zones. Close to Murchio Gap (Fig. 3; also, near p(3) on Fig. 4) metagraywackes display a gneissic foliation and NW-dipping, mm-cm–scale intrafolial folds, S-C fabrics, and C′ shear bands (Fig. 5). Some streaks and grooves are present on schistosity planes, and lineation trends range from northwest to west-southwest. Flattened mm-cm–scale fragments of sandstone are present in some exposures (e.g., at p(1) and p(2), Fig. 4). Conjugate joints (dipping northeast-southwest) (Fig. DR1[1]) and rare quartz veins crosscut the foliation.

Under the microscope, the foliation is defined by flattened quartz, aligned white mica, and feldspar. Based on the metamorphic assemblage that also includes lawsonite and jadeite in some samples, the feldspar appears to be albite. Chlorite is accessory.

Strongly foliated samples exhibit mica around rotated clasts and S-C fabrics that indicate sense of shear. Pressure solution seams and deformation lamellae are present within quartz and plagioclase grains, respectively. Most grains show undulose extinction as well as subgrain development and recrystallization. In samples taken close to the southwest boundary of the study area (near p(2) on Fig. 4), and north, northwest, and west of Juniper Camp, foliation is not penetrative. Quartz grains are cracked (Fig. DR2) and lack undulose extinction; plagioclase exhibits twinning lamellae.

Chert

Chert is typically red or green, with bed thicknesses up to 30 cm. Irregularly spaced schistose domains generally dip NW and are cut by quartz veins (≤1 mm thick). Axial surfaces of isoclinal folds have dip directions from north to west and are subparallel to the common foliation. Noncylindrical folds are rare. Quartz grains in the chert are typically elongated, and formerly round components in the grains are flattened. We interpret the latter as completely recrystallized radiolarians. Quartz grains show undulose extinction and recovery features such as subgrains with high-angle boundaries and recrystallized grains.

[1]GSA Data Repository Item 2008004, two tables with structural measurements and fault-slip data, photographs documenting macro- and microstructural deformation, and orientation of basalt flows and diabase dikes, is available at www.geosociety.org/pubs/ft2007.htm. Requests may also be sent to editing@geosociety.org.

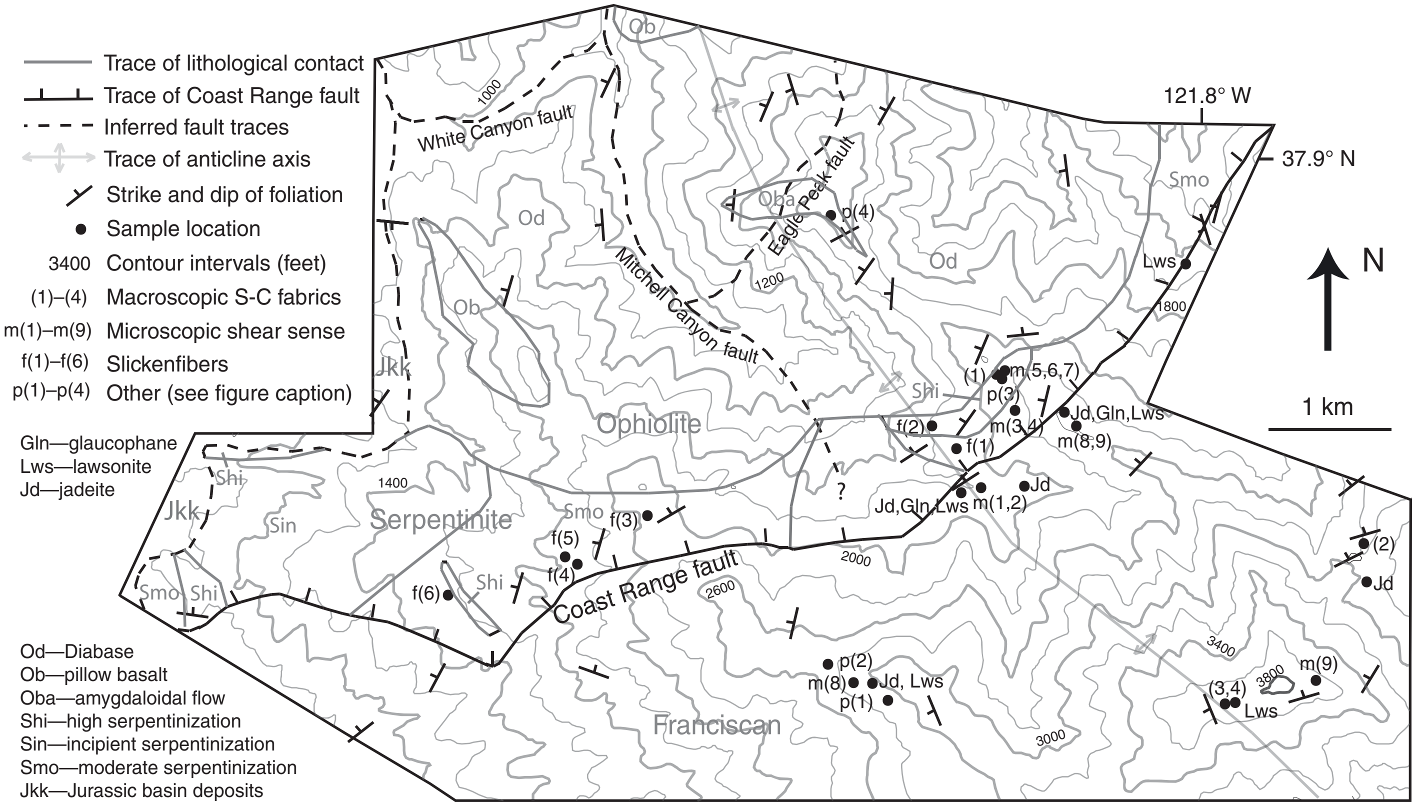

Figure 4. Structural map of the study area with locations of the main foliation orientations with dip directions (one symbol stands for an average orientation of several measurements in the vicinity of respective locations). Lithological contacts are contoured dark gray. Marked by a point are exposures of macroscopic S-C fabrics (1)–(4); positions of samples with microscopic shear-sense indicators m(1)–m(9); locations of serpentinite slickenfibers f(1)–f(6); p(1)—conjugate fault system (Fig. DR1), p(2)—cracked grains in metasediments (Fig. DR2), p(3)—outcrop with numerous orientations of slickenfibers for fault-slip analysis (Fig. DR6), and p(4)—sample with aligned plagioclase needles (Fig. DR3). Contour lines in the background indicate elevation changes of 200 feet.

Chert is locally interbedded with shale. Foliation in the latter is defined by aligned clay minerals and thick, flattened, quartz microlithons. Boundaries of quartz grains show effects of pressure solution. Undulose extinction is common, as are both polygonized and recrystallized grains.

Greenstone

Greenstone of the Franciscan Complex exhibits a foliation of curviplanar schistosity or cleavage that dips 40° to 80° N to W. Relict pillow structures are visible in some outcrops (e.g., northwest of North Peak). Conjugate joints crosscut the foliation, generally dipping northeast-southwest. A few carbonate spots within the rocks probably represent former calcite vesicles that now have mobilized into little veins. Because the foliation is not penetrative, these spots have typically not been flattened.

Lath-shaped crystals of albite are embedded as microlites within a cryptocrystalline groundmass of white mica, chlorite, and plagioclase. Pumpellyite and lawsonite are common. In some samples, glaucophane and jadeite are present. Deformation lamellae are common in albite. A penetrative schistosity is not well developed, but acicular minerals display a preferred orientation.

Structure, Degree of Deformation, and Metamorphism

Observed foliation includes anastomosing cleavage, partly to fully penetrative schistosity, and gneissic foliation. The foliation generally dips N to W with the following local exceptions (Fig. 4): (1) in the western part of the study area, where foliation dips 25–55° west-northwest; (2) along Bald Ridge, where foliation dips 70–90° north to northwest; (3) northeast of Bald Ridge, where foliation dips 40–60° west-southwest to west; and (4) foliation near the serpentinite band in the southwest part of the study area, where foliation dips range from northwest to north-northeast with increasing distance from the serpentinite band (Fig. 6). Axial surfaces of cylindrical folds in the chert are subparallel to the foliation.

Lineations are preferentially found in metasediments and have trends ranging from the north-northwest to west-southwest (Fig. 6). The lineations are defined either by streaks or grooves on foliation planes or by elongated clasts in metasandstones. Both macroscopic and microscopic S-C fabrics have developed in some metasediment exposures. Orientation data are summarized in Table DR1 (Data Repository). A set of conjugate joints typically crosscuts the foliation and older fabrics in the greenstone and metasediments. The conjugate joints generally dip northeast-southwest, but orientations vary depending on their position with respect to the doubly plunging anticline axis as follows: (1) southeast of the crest, northeast orientations can change to east-southeast and southwest orientations dip to south-southeast, and (2) northwest of the crest, northeast orientations dip north-northwest, and southwest orientations dip west-northwest.

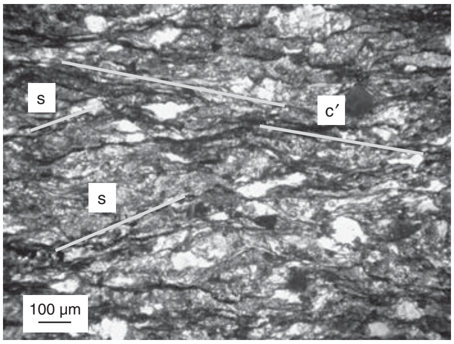

Figure 5. Kinematic indicators (C′ shear bands) within the metagraywacke (location p(3), Fig. 4). The strike of the thin section is approximately SE-NW (left-right).

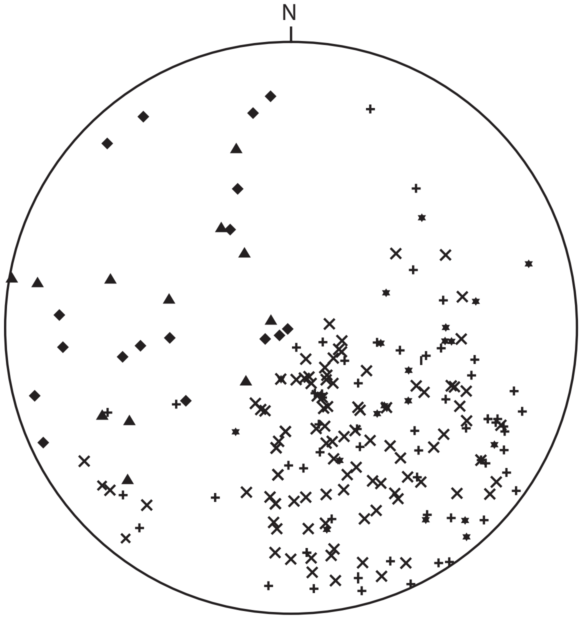

Figure 6. Orientations of foliations (poles to planes) and lineations within the three structural units.

In general, mineral grains (especially quartz) show deformational fabrics such as undulose extinction, deformation lamellae, and pressure solution. Development of subgrains (polygonization), in some cases with high-angle boundaries, cracked grains, and recrystallized grains, is indicative of recovery processes. These textural indicators of stress and recovery are commonly preserved within the same thin sections. Recovered grains may also be flattened and stretched within the preferred orientation. This implies that processes of recovery were syndeformational and postdeformational.

Metamorphic index minerals of the blueschist facies include jadeite, lawsonite, and glaucophane in some greenstone samples; and albite, white mica, and quartz with lawsonite and rare jadeite in coherent metasediments. Jadeite and pumpellyite were also found by Williams (1983a) in greenstone along Deer Flat Creek.

In the absence of albite, jadeite indicates pressures >10 kbar (Newton and Smith, 1967), depending on temperature and chemical composition. However, pressure estimates for the blueschist facies of the Franciscan Complex range from 6.5 to 9 kbar (Maruyama and Liou, 1988; Blake et al., 1988; Ernst, 1993), and locally from 7 to 8 kbar for exposures in the Northern Diablo Range (Ernst, 1993), corresponding to a minimum depth estimate of ~20 km. This is true for the coherent units (as at Mount Diablo), whereas the blocks in the mélange can have attained different metamorphic degrees (e.g., eclogite facies) up to 12 kbar, or amphibolite facies (Wakabayashi, 1990, 1992). None of the high-P metamorphic minerals make up kinematic indicators such as the S-C fabrics but are rather rotated into the foliation (Fig. 7A–B); therefore, metamorphism must have taken place before the deformation that records the fault kinematics.

COAST RANGE OPHIOLITE

The Mount Diablo ophiolite in the study area comprises diabase, amygdaloidal flows of uncertain composition, basalt flows, intrusions variously interpreted as sheeted dikes (Williams, 1983a, 1983b, 1984) or sheeted sills, (Hagstrum and Jones, 1998) and serpentinized ultramafic rocks. These rocks are described in detail as follows.

Diabase

The diabase contains dominant plagioclase either as partly recrystallized lathlike phenocrysts or cryptocrystalline groundmass. Augite, where not completely altered, shows undulose extinction. Quartz grains are polygonized into subgrains, some of which have high-angle boundaries. We interpret that the original texture must have been ophitic, although only a few pyroxenes are preserved. Epidote and chlorite are minor. Williams (1983a) also reported the presence of accessory prehnite, pumpellyite, and zeolites in the diabase. None of the minerals are aligned in a preferred orientation. The diabase is strongly fractured and exhibits a spaced cleavage, which represents the dominant foliation. This foliation, which is not always penetrative, is approximately subparallel to the main trend of the foliation in the Franciscan Complex and the serpentinite structurally below (Fig. 6).

Pillow Basalt

Round macroscopic structures (“pillows”) typical of pillow basalt are present in the ophiolite, but distinct planar paleohorizontal elements are rare. Flow structures and other criteria of stratigraphic top and bottom have been reported in the Mount Diablo area by Williams (1983a), Mankinen et al. (1991), and Hagstrum and Jones (1998), but these authors do not agree on the orientation of the structures.

Plagioclase makes up the groundmass of the pillow basalt but is also present as lath-shaped grains of all sizes; most of them are anhedral. Additionally, they show both undulose extinction and primary growth zonation. Plagioclase is partly replaced by epidote. Augite in the pillow basalt displays dissolved grain boundaries and is partially replaced by actinolite. The texture is subophitic to felty; poorly aligned plagioclase needles wrap around calcite vesicles and indicate flow structures. Calcite shows idiomorphic rhombohedrons and cleavage lamellae but is also locally polygonized.

Amygdaloidal Flow

The amygdaloidal flow contains either epidote or quartz amygdules with diameters of 1–8 mm embedded in a fine, green or gray crystalline groundmass of plagioclase, which is also present as lath-shaped microlites showing both twinning and deformation lamellae. Small plagioclase needles are slightly aligned, but they do not always wrap around the amygdules (Fig. DR3). Flattened amygdules contain cores of epidote and rims of feldspar or quartz; quartz grains show features of pressure solution, polygonization, and recrystallization. Rare cleavage represents the macroscopic foliation, which is characterized microscopi-

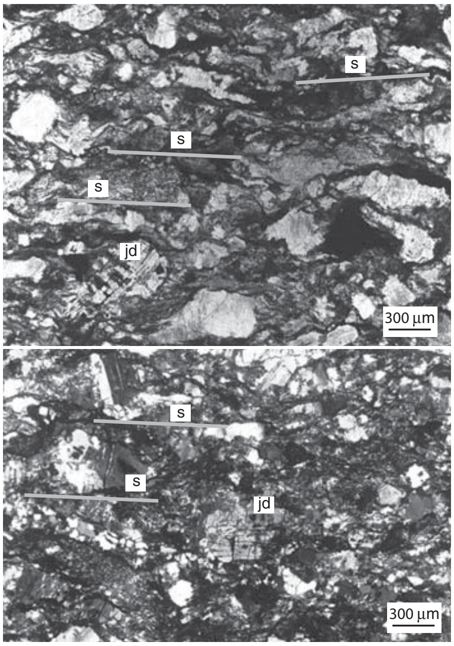

Figure 7. Both (A) and (B) show jadeite grains (jd), which are not flattened and aligned within the common foliation (which is parallel to the upper side of thin section), but rather rotated.

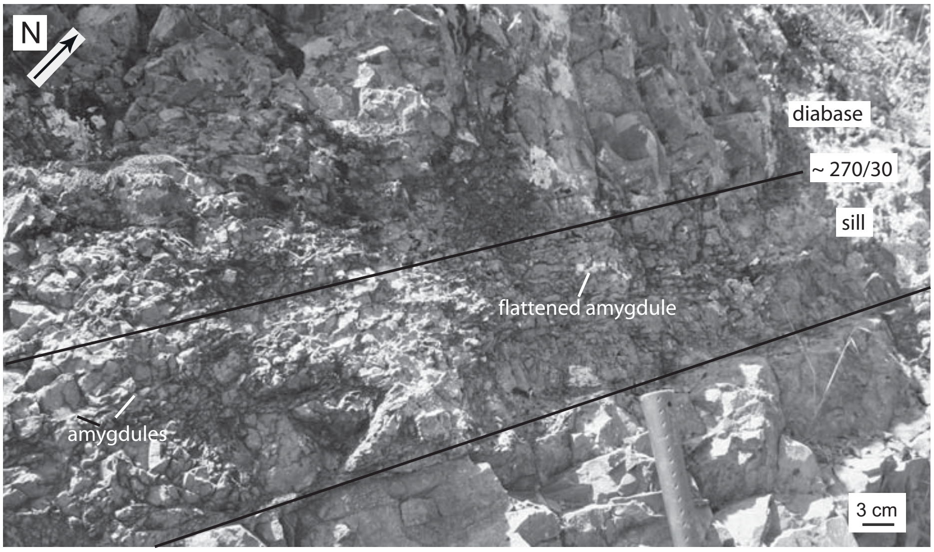

Figure 8. Flattened calcite amygdules in a sheeted sill. Flattening plane is parallel to the intrusive contact of the sill (dipping NW at an angle of ~30°).

cally by flattened amygdules. In contrast, plagioclase needles possibly represent primary flow structures.

Other Intrusives

Two different sets of intrusives can be observed in cliff exposures on Eagle Peak when viewed toward the northeast. One has a layered, leucocratic appearance and has an average dip of ~30° to the northwest, and the other is dark and almost perpendicular to the first (cf. Figs. DR4 and DR5). A sill with an orientation of 270/30 is found close to Twin Peak summit. It has flattened calcite amygdules, the orientation of which is again the same as the attitude of the sill itself (Fig. 8). We infer that the sill is an indicator of paleohorizontal, to which the flattening plane is subhorizontal.

Structure, Degree of Deformation, and Metamorphism

Deformation in the mafic rocks at Mount Diablo is only locally penetrative. The macroscopic deformation is characterized by a spaced cleavage and associated fractures. Microscopically, it consists of flattened amygdules, quartz grains, and feldspar of the amygdaloidal flow, also affected by pressure solution.

The orientation of the sills with flattened calcite amygdules, as well as the aligned plagioclase needles in the pillow basalt and macroscopic flow structures (Hagstrum and Jones, 1998) have a dip direction to the west-northwest. These primary features indicate paleohorizontal, to which secondary deformation fabrics such as cleavage in the diabase and the common foliation within Franciscan rocks are subparallel, but with a slightly lower dip angle.

Flow structures, deformation, and mineral assemblage are likely to be related to seafloor spreading, which preceded deformation during subduction. Uralite, chlorite, albitized plagioclase, and epidote indicate greenschist metamorphism related to hydrothermal alteration near the spreading center. Prehnite, pumpellyite, and zeolite indicate even lower grade metamorphism, probably due to burial metamorphism (Williams, 1983a). Common pressure estimates for the greenschist facies are ~3–6 kbar; thus, a local estimate for the missing section between the blueschist Franciscan and the greenschist Coast Range ophiolite across the Coast Range fault ranges between 6 and 18 km.

SERPENTINITE/ULTRAMAFICS

The band of serpentinite represents the lower remnant component of the ophiolite and marks the structural contact between the ophiolite and the Franciscan Complex. The ophiolite provides key kinematic data for interpreting motion along the Coast Range fault, because it was pervasively sheared during the activity of the Coast Range fault. It consists of variably deformed and serpentinized ultramafic rocks and locally forms schist in the shear zones at Murchio Gap and Prospector's Gap. One outcrop at Murchio Gap exposes variously oriented straight slickenfibers, each with a microshear plane. Slickenlines and slickenfibers both trend northwest-SE (stepping down to the northwest).

Antigorite and chrysotile were identified in samples from the study area by X-ray diffractometry. Microscopically, the "bladed-mat" texture indicates the presence of antigorite (O'Hanley, 1996), which in our study area forms blades that are aligned within a preferred NW-trending orientation.

The veins in the serpentinite are amorphous picrolite veins or fibrous chrysotile veins (O'Hanley, 1996; Wicks and O'Hanley, 1988). No clear relation between them exists, but amorphous veins appear to be more common on NW-dipping cleavage planes than the fibrous veins. The latter make up the vein system in the ultramafics, whereas picrolite is found in highly serpentinized rocks. In some outcrops, fibrous serpentinite can be found in the core of picrolite veins, which suggests that it formed at a later stage. Magnetite is accessory (~2%–6%).

Ultramafics

Ultramafic rocks in the study region (mostly harzburgite, but also pyroxenite; Pampeyan, 1963) have developed a spaced cleavage generally dipping northwest (Fig. 6), similar to the cleavage systems in the other ophiolite units. Slickenfibers on some of these cleavage planes commonly step up to the SE, indicating top-to-the-NW motion. Joints dip NE and SW, subparallel to the orientations of joints found in Franciscan lithologies.

The degree of serpentinization and the symmetry of the vein system are indicators of the relative amount of deformation that the ultramafic rocks have experienced (Wicks and O'Hanley, 1988). Pyroxenite, found close to the Great Valley Group strata in the SW study area, is only slightly serpentinized. In ultramafic rocks subject to minor deformation (termed "incipient" serpentinization, Fig. 4), serpentinization characteristically displays a "mesh texture," where serpentine minerals form narrow bands around cores of unaltered olivine grains (Maltman, 1978). Veins do not form a symmetric system. Rocks subjected to higher strains exhibit a more rectangular vein system with regular spacing, which developed along the cleavage planes. Microscopically, mesh cells with cores are further flattened, forming "ribbons" at the expense of the cores ("moderate" serpentinization, Fig. 4). In some cases, the ribbons form parallel bands. This fabric is only observed near the shear zones, where serpentinization is complete ("high" serpentinization, Fig. 4).

Antigorite Schist

The serpentinite schist, mostly comprised of antigorite, but also chrysotile, has a well-developed NW-dipping schistosity (Fig. 6). S-C fabrics have developed within the shear zones (Fig. 9; Table DR1). In thin section, the microcrystalline antigorite blades show the same texture as the strongly serpentinized ultramafics described above. Aligned blades form the foliation and partly wrap around serpentinite clasts. Dissolution seams have formed at the grain boundaries of some clasts. Broken or imbricated clasts indicate shear sense (Fig. 10).

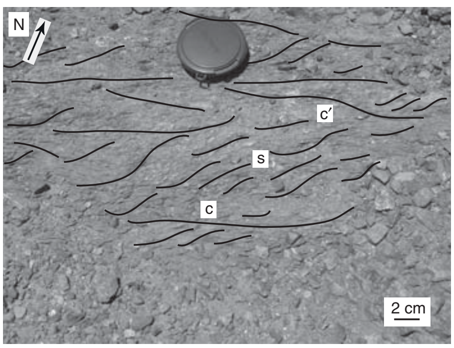

Figure 9. Macroscopic S-C fabrics in serpentinite schist (S—270/62, C—316/74, C′—334/79) at Murchio Gap (location (1), Fig. 4).

Structure, Degree of Deformation, and Metamorphism

The presence of antigorite and fabrics such as rotated clasts, S-C fabrics, and straight slickenfibers in shear zones, suggests that stable fault creep was the main mechanism that led to serpentinite deformation, which implies steady movement along the Coast Range fault. This is consistent with experimental studies (Reinen et al. 1991, 1992; Reinen, 2000). We attribute the difference in degree of serpentinization ("incipient," "moderate," and "high") to variations in strain and volume of fluids circulating along the fault.

Shear sense inferred from several indicators such as slickenfibers, rotated or imbricated clasts in antigorite schist, oblique ribbons, and macroscopic S-C fabrics (Fig. 9 and Table DR1) indicates top-to-the-NW/WNW motion in the present reference system. Both cleavage systems in the ultramafic rocks and foliations within the serpentinite dip primarily NW, subparallel to the flattened calcite amygdules in the sills, the sills themselves, the cleavage within the ophiolite, the main foliation within the Franciscan, and the orientation of the Coast Range fault itself (Fig. 6). NE- to SW-dipping joints are present in ultramafic rocks, similar to the conjugate joint system that crosscuts the foliation of Franciscan rocks.

Fault-Slip Analysis

Fifty measurements of slickenfibers and their respective shear planes in various orientations (fault-slip data) were taken from a coherent serpentinite outcrop within the shear zone at the northern end of Bald Ridge (Fig. 3). Slip sense was inferred for each slickenfiber with regard to the missing plane of the respective "hanging wall" from each microshear plane and was classified as normal, reverse, dextral, or sinistral. We used the program FLTSLP (R.J. Twiss and L. Guenther, University of California, Davis) to invert the fault-slip data for components of a reduced deformation rate tensor, which is parameterized by the orientations of the three principal strain rate axes ($d_1 > d_2 > d_3$; extension reckoned positive); the deformation rate parameter D (D = $(d_2 - d_3)/(d_1 - d_3)$), which defines the shape of the strain-rate ellipsoid; and the relative vorticity parameter W, which is the difference between the rotation rate of individual fault-bounded blocks and the continuum macrovorticity, resolved about the d_2 axis (Twiss and Gefell, 1990; Twiss et al., 1991). The inversion results indicate that d_1 plunges moderately to the west-northwest, d_3 plunges moderately to the ESE, and d_2 is subhorizontal and trends north-northeast. The best-fit value of D is ~0.55, which indicates progressive flattening for a constant volume deformation (with the caveat that flattening cannot, in this case, be distinguished from a plane strain [D = 0.5] at the 95% confidence level). The value of W is less than zero at the 95% confidence interval, indicating that the vorticity of fault-bounded blocks within the shear zone is less than the macrorotation rate (Twiss et al., 1991; Twiss and Unruh, 1998). Although many kinematic models for a negative value of W are possible, this result could indicate that the long dimensions of fault-bounded blocks within the serpentinite were parallel to the direction of shear and thus were geometrically incapable of rotating at the full continuum macrovorticity associated with the rate of shearing across the entire zone (see discussion of the kinematic significance of W in Unruh et al., 1996).

We use the inversion results to evaluate the direction of maximum resolved shear on the Coast Range fault associated with the best-fit deformation geometry. To perform this analysis, we first determine the orientation of the Coast Range fault. Measured off the map, the local strike of the Coast Range fault in the vicinity of the coherent serpentinite outcrop is northeast-southwest (53°–233°); the average strike of the serpentinite band across the extent of the study area ranges from ~50°–230° to 70°–250°. From measurements of topographic relief on the base of the serpentinite band, we estimate that the dip of the Coast Range fault is consistent with its outcrop pattern with a dip angle between 30° NW and 50° NW. This range in dip angle is comparable to the dip of bedding in the structurally overlying Great Valley Group strata located ~2 km to the northeast and southwest of the serpentinite outcrop (Dibblee, 1980).

We use the best-fit inversion parameters and the algorithm SLPLIN (R.J. Twiss, University of California, Davis) to determine the

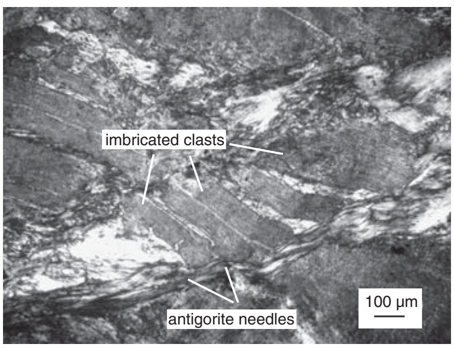

Figure 10. Imbricate clasts in antigorite schist indicate shear-sense to the NNW (upper left corner of thin section), (location m(7), Fig. 4).

direction of maximum resolved rate of shear on a variety of shear planes spanning the ranges in strike and dip estimated for the Coast Range fault in our field area (Fig. 11D). SLPLIN calculates the tensor product between the reduced deformation rate tensor and a unit vector normal to a specified shear plane. The result is a new vector that in general has a different orientation than the unit normal to the shear plane. The change in orientation from the unit normal resolved on the shear plane gives the direction of maximum resolved shear rate. We assume that slip occurred in the direction of maximum resolved shear rate during deformation. The results consistently indicate top-to-the-NW motion along the Coast Range fault in the present reference frame. In general, the direction of maximum resolved shear rate on faults dipping 40° to 50° indicates nearly pure dip-slip motion. The direction of maximum resolved shear rate on faults dipping ~30° indicates right-oblique slip but is dominantly normal.

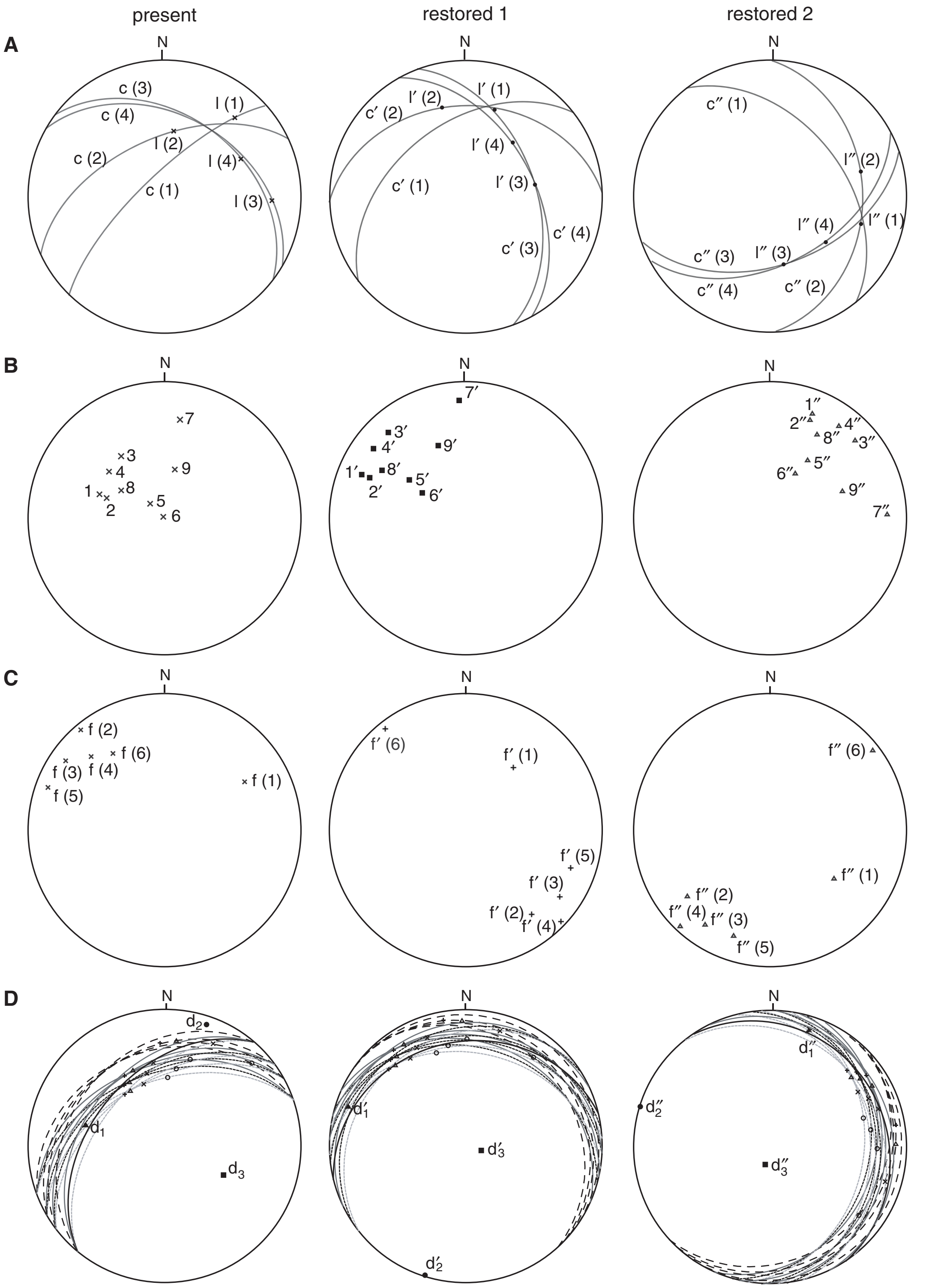

Figure 11. Stereoplots with orientations of (A) macroscopic S-C fabrics (lineation determined from the intersection of s and c when lineation not obvious in the field), location (1) antigorite schist, (2)–(4) metasediments (Fig. 4), (B) microscopic shear-sense indicators (points indicate the direction of "top-to," thin sections are parallel to lineations), (C) serpentinite slickenfibers (points indicate the direction of stepping down), and (D) orientation data from the fault-slip analysis. The left column shows orientations in the present position; the center column depicts orientations after the first step of restoration (tilting 30° clockwise around the strike of the Coast Range fault—a horizontal axis trending NE [030/00]); the right column shows orientations after the second restoration step (rotating 90° clockwise around a vertical axis). (D) Orientations of a range of shear planes (great circles) with associated directions of maximum shear (symbols vary according to the tested dip angle of the shear plane) tested in the analysis with SLPLIN. For most of the tested possibilities, maximum resolved shear was top-to-the-NWN in the present reference frame. See the text for more details. Orientation data are summed up in Tables DR1 and DR2.

Within the range of fault orientations we consider, the obliquity of the resolved rate of shear is less sensitive to variations in the strike of the Coast Range fault than the dip.

Based on the results of the kinematic inversion, we interpret movement along the Coast Range fault to have been top-to-the-NW (331/45) in the current reference frame, consistent with motion recorded by previously described shear-sense indicators in the serpentinite and the Franciscan metasediments.

TECTONIC IMPLICATIONS

Restoration of Original Attitude of the Coast Range Fault

Paleomagnetic analyses of the ophiolite at Mount Diablo by Williams (1983a), Mankinen et al. (1991), and Hagstrum and Jones (1998) indicate that the unit has been rotated and tilted. However, these authors disagree on whether the sheeted intrusives are sills or dikes, and thus, they infer different rotation histories. We found leucocratic sheeted sills (cf. Figs. DR4 and DR5) with an average orientation dipping to the NW and a dip angle of ~30° (similar to sheeted intrusives measured by Hagstrum and Jones, 1998). These leucocratic sills have the same orientation as diabase dikelets described by Williams (1983a), whereas her leucocratic dikelets have a similar attitude to our diabase dikes (almost perpendicular to each other). We reinterpret the leucocratic sills of Williams (1983a) to be dikes and vice versa. If this is correct, then Williams' (1983a) observations bearing on paleohorizontal are consistent with ours and those of Hagstrum and Jones (1998). We also found flattened calcite amygdules in one sill, the flattening plane for which is parallel to the sill itself (namely 270/30). The average orientation of the sills is ~300/30. Thus, the foliations in the ophiolite, serpentinite, and Franciscan are subhorizontal, as well as the Coast Range fault, and they have the same orientation as the primary flow structures. This present dip of these features represents tilting of the paleohorizontal surface. This tilting must be restored; therefore, all units are rotated ~30° appropriately about a horizontal axis parallel to the average present strike of the flow structures (NE trend [030/00]).

Following restoration of the present dip, the kinematic indicators within the serpentinite band retain a top-to-the-NW sense of shear along a low-angle fault (Fig. 11A–D, center column). We acknowledge that this restoration approach is a simplification, because the paleohorizontal flow structures may have been tilted already before attaining their present orientation at Mount Diablo.

Williams (1983a) inferred a 70° (pre-4 Ma) + 30° (post-4 Ma) counterclockwise rotation of Mount Diablo around a vertical axis based on the assumption that the serpentinite band connecting the Concord fault and the Riggs Canyon fault originally had a trend of N-S (Fig. 2), similar to the regional trend of the Coast Range fault elsewhere in California (see also Ingersoll, 1979).

If this assumption is correct, then shear-sense data should be additionally restored by clockwise rotation around a vertical axis. We use 90° rather than Williams' (1983a) proposed 100° of counterclockwise rotation (CCW), because this rotation better matches the local strike of the Coast Range fault in the study area. This second back rotation restores to a low angle Coast Range fault dipping to the NE with kinematic indicators yielding a top-to-the-NEE sense of motion (Fig. 11A–D, right column).

The interpretation that the present ENE strike of the Coast Range fault in our study area is a result of CCW rotation from an assumed original N-S strike (Williams, 1983a) is problematic because the structural contact separating the high P/T Franciscan Complex from all overlying lower-grade rocks, including both the serpentinite and Great Valley Group, actually crops out as an irregular ellipse because it is folded about the axis of Mount Diablo anticline (Fig. 2). These present map-scale relations are more simply and parsimoniously explained by folding of an originally subhorizontal to gently east-dipping surface about a WNW-trending axis, rather than CCW rotation about a vertical axis. If this interpretation is correct, then the 30° of post-4 Ma, CCW vertical-axis rotation inferred by Williams (1983a) need not be restored from the present orientation of the Coast Range fault, and the original dip direction of the fault was likely to the NE.

Although the magnitude and direction of vertical axis rotation at Mount Diablo is uncertain, the data indicate even in the current reference frame that the fault zone accommodated net attenuation and that the ophiolite moved in a normal sense of shear relative to the high-pressure Franciscan Complex rocks discussed in the next section.

Deformational Processes

Two structural units of different metamorphic degree are found in structural contact at Mount Diablo. The presence of glaucophane, jadeite, and albite in coherent units of the Franciscan indicate blueschist facies, whereas minerals such as epidote, and both prehnite and pumpellyite, in the ophiolite characterize greenschist-facies metamorphism and lower. The metamorphic section that is missing across the Coast Range fault at Mount Diablo is thus ~6–18 km. The structural juxtaposition of these units eliminates nontectonic exhumation mechanisms from consideration and indicates that extensional processes or out-of-sequence thrusting, rather than erosion, accommodated exhumation of the high P/T rocks.

The foliation fabrics in the Franciscan rocks, the serpentinite band, and the ophiolite have a common average orientation dipping to the NW. The uniformity in foliation orientation supports the existence of coaxial flow and ductile thinning after underplating of the Franciscan rocks and during initial exhumation rather than during subduction. We infer that transport in a subduction channel and basal accretion would have created more scatter in orientations than we observe.

The fact that the Franciscan rocks are poorly lineated suggests internal flattening strain caused by ductile thinning during exhumation of the high P/T assemblage. Lineations present on foliation planes of Franciscan rocks are mostly attributed to sliding within the coherent units.

As discussed above, kinematic analysis of fault-slip data from the serpentinite band indicates both top-to-the-NW (normal-sense) shearing and attenuation normal to the macroscopic shear plane (i.e., normal to the Coast Range fault), which was kinematically linked to vertical thinning at lower structural levels (Unruh et al., 2007). We conclude that these two processes, rather than out-of-sequence thrusting, were primarily responsible for exhumation (Fig. 12).

Estimates for exhumation by ductile thinning in other orogens range from 20 km for the Alps (Selverstone, 1985) and Japan (Wallis, 1992, 1995) to 3.5 km for the Franciscan (Bolhar and Ring, 2001) and 13% for the Cascadia forearc region (Feehan and Brandon, 1999). For Mount Diablo, we cannot quantify the contribution of ductile thinning, but we assume that it is similar to or less than the estimate by Feehan and Brandon (1999), because with flattening strains, the mass-volume balance does not require high solution mass transfer. We observe evidence for pressure solution in our samples, but microscopic fabrics indicating dislocation creep or grain-boundary slip are inconsistent with solution mass transfer as the dominant deformation mechanism.

Slight scatter of foliation orientations and dip over the area ranging from about north-northeast to west-northwest (Fig. 6) and lineations plunging from north-northwest to west-southwest can probably be attributed to map-scale late Cenozoic (since ca. 4 Ma) antiformal folding. If the effect of the Plio-Pleistocene folding had been greater, we would expect the serpentinite band, which strikes parallel to the direction of

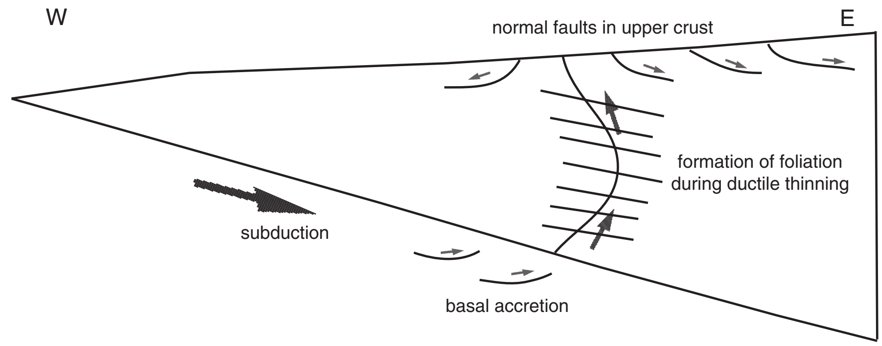

Figure 12. Deeply buried rocks attain a common foliation during uplift due to ductile thinning, which, together with normal faulting at lower structural level, contributes to the exhumation of blueschist-facies rocks (after Feehan and Brandon, 1999).

northeast-southwest shortening, to show more distinct evidence of folding. No such evidence was observed.

Relative Timing of Deformational Increments and Implications for the Coast Range Fault

Based on the observed structures, crosscutting relations, and post-exhumational deformation, we reconstruct the following geological history for the Mount Diablo study area:

(1) The blueschist mineral assemblage in the Franciscan Complex confirms that the rocks were subducted to depths of high P/T conditions. In contrast, units of the ophiolite have not been buried to great depth, and they were metamorphosed to a maximum of greenschist facies during hydrothermal alteration near an oceanic spreading center.
(2) Peak exhumation of Franciscan rocks at Mount Diablo took place from ca. 70–50 Ma (Unruh et al., 2007), which sets the relative age for the exhumation and syn-exhumational development of foliation and rare lineations in the Franciscan rocks at Mount Diablo.
(3) Activity on the Coast Range fault was coeval with development of the cleavage in Franciscan units and contributed to exhumation of high P/T Franciscan rocks, presumably at a higher structural level. Structures within the serpentinite band, such as S-C fabrics, shear bands, rotated clasts, and slickenfibers, record the fault activity. The serpentinite was sheared between the foliated Franciscan rocks and the relatively less deformed upper parts of the ophiolite. Foliation and flow structures in the Franciscan and the ophiolite are subparallel. The Coast Range fault accommodated net attenuation and normal motion of the Coast Range ophiolite relative to the structurally underlying Franciscan rocks.
(4) After the high P/T Franciscan rocks were juxtaposed against the lower grade ophiolite, all units were subject to rotation (~90° counterclockwise) and tilting (~30° toward the northwest) before attaining their present orientations.
(5) The system of conjugate joints (generally dipping west-southwest and east-northeast) crosscuts all other structures. Given their orientations, the joints probably formed in the same tectonic regime of northeast-southwest compression as Mount Diablo anticline or shortly before, because some joints show some deviation in orientation from the characteristic attitude.
(6) Since 4 Ma, Mount Diablo has undergone antiformal folding in a transpressional tectonic regime characterized by horizontal northeast-southwest maximum compression, which led to a slight scatter of orientations in all units (foliations, primary features, and conjugate joints).

CONCLUSIONS

This work synthesizes petrographical and structural observations with the goal of reconstructing the deformation history of the Franciscan subduction complex and its exhumed high P/T mineral assemblage within coherent units at Mount Diablo. Although the structural setting at Mount Diablo is complex, the kinematics of the Coast Range fault indicate that the Franciscan Complex moved up relative to the overlying ophiolite, and thus the fault accommodated net crustal attenuation. We interpret the dominant exhumation mechanism at Mount Diablo to be a combination of attenuational movement along the Coast Range fault as documented by fault-slip analysis and vertical thinning owing to ductile flow in the lower crust, which has produced a foliation common to all Franciscan blocks at Mount Diablo and a weakly developed lineation. The combination of these two processes represents a viable mechanism for the exhumation of Franciscan high P/T rocks. Similar mechanisms may have contributed to exhumation of high P/T rocks in other orogens.

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