Nappes, Tectonics of Oblique Plate Convergence, and Metamorphic Evolution Related to 140 Million Years of Continuous Subduction, Franciscan Complex, California

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ABSTRACT

This paper presents a new synthesis of Franciscan Complex tectonics, with the emphasis on the pre-San Andreas fault history of these rocks. Field relations suggest that the Franciscan is characterized by nappe structures that formed during sequential accretion at the trench. The presence of these structures along with other field relations, including the lack of evidence for large offset of conglomerate suites, indicates that strike-slip fault systems of large displacement (>500 km) did not cut the Franciscan Complex during subduction. Regional geology and comparisons to modern arc-trench systems suggest that strike-slip faulting associated with oblique subduction took place inboard [east] of the Franciscan in the vicinity of the magmatic arc. The Franciscan varies along strike, because individual accreted elements [packets of trench sediment, seamounts, etc.] did not extend the full length of the trench. Different depths of underplating, distribution of post-metamorphic faulting, and level of erosion produced the present-day surface distribution of high P/T metamorphism. Franciscan Complex tectonic history can be summarized as follows: [1] East-dipping Franciscan subduction initiated beneath, and shortly after formation of, the Coast Range ophiolite. [2] High-temperature precursors to Franciscan high-grade tectonic blocks formed as a dynamothermal aureole during subduction initiation beneath the hot hanging wall and were underplated to the upper plate. [3] Subduction continued, the high-grade metamorphic rocks were overprinted with assemblages of increasing P/T ratio as the hanging wall cooled, and the aureole was dismembered into blocks. [4] As subduction progressed, more material was underplated and metamorphosed as coherent blueschist. Peak metamorphic temperatures of successively subducted units decreased with time as hanging wall heat continued to dissipate. [5] Trench sediments with parts of seamounts, oceanic rises, and other small masses on the downgoing plate were underplated or offscraped during approximately 140 m.y. of continuous subduction, forming stacks of nappes. [6] The Mendocino Triple Junction migrated northward, and the subduction zone was replaced by a transform plate boundary associated with the San Andreas fault. Deformation and faulting related to the Neogene transform tectonic regime obscured many subduction-related structures.

Introduction

The Franciscan Complex of the California Coast Ranges is an assemblage of variably deformed and metamorphosed rock units that formed as a subduction complex associated with east-dipping subduction at the western North American margin from the late Jurassic through the Tertiary, a period of over 140 m.y. [e.g., Hamilton 1969; Page 1981]. Franciscan lithologies are predominantly detrital sedimentary rocks with subordinate basaltic volcanic rocks and chert, and minor limestone. The detrital rocks may represent offscraped and underplated trench-fill sediments [e.g., Dickinson 1970]. The pelagic and volcanic rocks may represent fragments of seamounts, other oceanic rises, and the pelagic cover and upper part of the subducted oceanic crust [e.g., Hamilton 1969; MacPherson 1983; Tarduno et al. 1985], possibly with a component of olistostrome blocks from the upper plate [MacPherson et al. 1990].

The Franciscan is well known for high P/T metamorphism [e.g., Ernst et al. 1970; Ernst 1970, 1971]. The Coast Range ophiolite structurally overlies the Franciscan and is depositionally overlain by well-bedded sandstones and shales of the Great Valley sequence coeval with the Franciscan [e.g., Dickinson 1970]. The Coast Range ophiolite and Great Valley sequence lack high P/T metamorphism. From west to east, the three sub-parallel geologic provinces of the Franciscan, Great Valley

1 Manuscript received May 1, 1991; accepted August 18, 1991.
sequence, and Sierra Nevada batholith (see Figure 1) may represent respectively the subduction complex, forearc basin deposits, and arc of an ancient arc-trench system [e.g., Dickinson 1970, Ingersoll 1978]. Few dispute this general model, but major questions and controversy regarding Franciscan history remain, for example: (1) Disagreement exists over whether or not large-scale (>500 km) strike-slip faulting took place within the Franciscan (e.g., McLaughlin et al. 1988, in favor; Seiders 1991 against). (2) The structural relationship of many Franciscan tectonostratigraphic terranes to one another is poorly understood. (3) Opinions differ on whether coarse-grained blueschist, eclogite, and amphibolite tectonic blocks [called “high-grade blocks” or “knockers” in Franciscan litera-
ture] are vestiges of a pre-Franciscan metamorphic event [e.g., Coleman and Lanphere 1971; Blake et al. 1988] or instead formed during the initial stages of Franciscan subduction [e.g., Platt 1975; Suppe and Foland 1978; Cloos 1985; Wakabayashi 1990].

In this paper the above problems and other aspects of Franciscan geology will be evaluated including: (1) the occurrence and significance of low-angle faults that formed during subduction and accretion, particularly those separating Franciscan tectonostratigraphic terranes; (2) obliquity of plate convergence and its consequences in Franciscan tectonics; (3) metamorphism and its relationship to tectonic evolution; and (4) aspects of Franciscan accretion that may not fit a “classical” [e.g., Karig and Sharman 1975] model of accretion, such as tectonic wedging [e.g., Wentworth et al. 1984] and distribution of high-grade blocks [a problem that bears on the mechanisms of Franciscan melange formation].

The Franciscan Complex: Regional Overview

The present outcrop pattern and structure of Franciscan rocks has been heavily influenced by Neogene faulting and deformation that initiated [and continues to the present] after east-dipping Franciscan subduction ceased and was replaced by a dextral transform fault plate boundary represented by the San Andreas and related strike-slip faults [figure 1]. Considerable folding and dip-slip faulting has accompanied the strike-slip faulting [e.g., Page 1981]. In this paper, an attempt is made to “see through” this later deformational overprint and evaluate the subduction history of the Franciscan Complex by focusing on features that have largely escaped disruption by the later event.

Within the Franciscan Complex are numerous fault-bounded units, each with distinctive lithology, age, metamorphism, and structure, that have been termed “tectonostratigraphic terranes” [e.g., Blake et al. 1982]. Names of units discussed in this paper follow Franciscan terrane nomenclature of Blake et al. (1982) except for composite or previously unnamed terranes [for brief descriptions of various Franciscan terranes discussed in this paper see table 1, in the Depository File, available free of charge upon request from The Journal of Geology]. The Franciscan can be divided into four regions [fig. 1] that differ in structural and lithologic character: (1) the northern Coast Ranges; (2) the region between the San Andreas and Hayward/Healdsburg-Rodgers Creek faults; (3) the Diablo Range; and (4) the Nacimiento block [Sur terrane of McWilliams and Howell 1982].

1) Northern Coast Ranges. In this region, the Franciscan has traditionally been subdivided into three NW-SE trending lithologic belts: the Eastern, Central, and Coastal belts [Berkland et al. 1972]. Easternmost and structurally highest, the blueschist grade Eastern Belt consists of thrust sheets of metaclastic and metavolcanic rocks with fine-grained metamorphic minerals generally <0.2 mm in size [Suppe 1973; Worrall 1981; Blake et al. 1988]. The belt has been divided into the structurally highest and highest metamorphic grade Pickett Peak terrane, schistose rocks commonly with complete textural reconstitution, and the structurally lower Yolla Bolly terrane, unfoliated to foliated rocks with variable preservation of protolith textures [Blake et al. 1982]. The Yolla Bolly terrane also includes a subunit of shale matrix melange [Worrall 1981; Jayko and Blake 1989]. Yolla Bolly terrane metaclastic rocks have yielded Tithonian to Campanian fossils [Blake et al. 1988]. Eastern Belt and similar rocks are referred to as “coherent blueschists” in this paper. Among coherent non-melange Franciscan rock units, only the coherent blueschists exhibit penetrative fabrics, with the exception of local weakly-developed foliation in some sandstones.

The Central Belt lies west of and structurally below the Eastern Belt and contains a large proportion of shale matrix melange that includes blocks of varying lithologies and metamorphic grades [Hsü 1968; Gucwa 1974; Cloos 1982; Blake et al. 1988]. The boundary between the Eastern and Central belts is somewhat ill-defined, and Seiders [1991] has mapped conglomerate units that strike across the previously defined boundary without apparent offset. The Central Belt includes units of largely coherent internal structure ranging up to tens of kilometers in size. Detrital rocks of these coherent units have yielded fossils ranging from Tithonian to Campanian in age [Blake et al. 1984, 1988]. Franciscan melange matrix displays a strong shear fabric, and most Franciscan melanges, including those in the Eastern and Coastal Belts, appear to have functioned as shear zones during part of their history [e.g., Cloos 1982]. Some Franciscan melanges may have originated as olistostromes that were subsequently subducted [e.g., Aalto and Murphy 1984; Cowan 1985; MacPherson et al. 1990]. Few studies have been conducted on Franciscan melange matrix mineralogy, but lawsonite identified in some samples suggests at least local high P/T metamorphism of the matrix [Cloos 1983], and paleotemperature studies are consistent
with deep burial (>10 km) of some of the melanges [Underwood et al. 1988]. Metamorphism of melange matrix and included blocks of various metamorphic grades may suggest circulation of melange to variable depths and return flow [e.g., Cloos 1982, 1984]. Most coherent units within the Central Belt are of prehnite-pumpellyite grade [Blake et al. 1984, 1988].

The Coastal Belt (including the Yager terrane of Underwood and Bachman 1985), the westernmost of these three Franciscan belts, structurally underlies the Central Belt [Bachman 1978; Blake et al. 1988]. The Coastal Belt is composed of variably deformed sandstone and shale, including melange units, with minor basalt, limestone, and chert and is of mostly zeolite grade [Bachman 1978; Blake et al. 1988]. Excluding pelagic rocks, the Coastal Belt contains fossils ranging in age from Paleocene to Miocene [Blake et al. 1988].

2) San Francisco Block. The region bounded roughly by the San Andreas, Hayward, and Healdsburg-Rodgers Creek faults, herein called the San Francisco block. In this region, the Franciscan comprises a stack of nappes composed of coherent terranes of varying lithology and metamorphic grade, separated by low-angle melange zones [Blake et al. 1984; Wakabayashi and Moores 1988b; Wakabayashi 1989]. Melange is subordinate to coherent units in much of this area. With the exception of locally severe deformation near the San Andreas fault [Page 1981], this domain may be the least affected by Neogene deformation of any region in the Coast Ranges [Herd 1978; Fox 1983], and as such provides a good field area to examine Franciscan field relations that may have resulted from subduction. The nappes of this region have been gently folded about NW-SE subhorizontal axes. Erosion has produced the present-day map pattern of belt-like rock units with their long axes oriented parallel to those fold axes. One of the more notable rock units is a coherent blueschist that resembles the structurally high, schistose, Pickett Peak terrane of the northern Coast Ranges, but is coarser-grained with metamorphic minerals up to 1 mm in size [Wakabayashi unpub. data]. The two largest exposures of this unit are a 17 × 4 km exposure [metabasalt and metagreywacke] near Cazadero [Coleman and Lee 1963; Erickson 1991] and a 70 × 3 km belt [mostly metagreywacke] that extends northwest from near Healdsburg [Bailey et al. 1964; Blake et al. 1971; Blake et al. 1984] (figures 1 and 4). These rocks will be informally referred to as the Skaggs Springs schists. The specific exposure of these schists near Cazadero, on which a number of petrologic studies have been conducted [e.g., Coleman and Lee 1963; Maruyama and Liou 1988], will also be referred to as the Ward Creek coherent blueschists.

3) Diablo Range. In the Diablo Range, slabs of metagreywacke, mostly of blueschist grade, are separated by melange zones that commonly contain high-grade blocks [Raymond 1973; Cotton 1972; Cowan 1974; Crawford 1975; Page 1981; Blake et al. 1984]. Some of the coherent slabs [the Eyllar Mountain terrane] have been correlated with the Yolla Bolly terrane of the Eastern Belt of the northern Coast Ranges [Blake et al. 1982], although these slabs exhibit more widespread crystallization of jadeitic pyroxene. South of the Diablo Range and east of the San Andreas fault, the Franciscan crops out in limited exposures consisting mainly of melange that locally contains high-grade blocks and serpentinite. The Diablo Range domain is bounded on the west by the San Andreas and Hayward faults. West of the San Andreas fault is the Salinian block, a 700 km × 70 km allochthonous slice of continental crust with granitic and high T/P metamorphic basement.

4) Nacimiento Block or Sur terrane. West of the Salinian block across the Sur-Nacimiento fault zone is a belt of Franciscan exposures composed primarily of melange [e.g., Hsü 1968; Page 1981; the Sur terrane of McWilliams and Howell 1982]. These rocks may have originated farther south along the western North American plate margin than the rest of the Franciscan based primarily on paleomagnetic data [e.g., Page 1982; McWilliams and Howell 1982; Vedder et al. 1983]. However, if Neogene strike slip displacement is undone [a palinspastic reconstruction that undoes Neogene strike-slip faulting is presented in Depository File, figure C], similar conglomerate compositions for Franciscan east of the San Andreas fault [the San Francisco block] and Sur terrane rocks suggest a linking of the two terranes [Seiders 1988; Seiders and Blome 1988]. In addition, the apparent latitudinal shift suggested by the paleomagnetic data has been questioned [Tarduno 1990; Butler et al. 1991].

Low-Angle Faults Related to Franciscan Subduction

The central San Francisco Bay region [Bay Area] of the San Francisco block preserves some of the best examples of low-angle tectonic contacts formed during Franciscan subduction and accretion. Franciscan rock units in this region comprise a stack of nappes [Blake et al. 1984; Wakabayashi and Moores 1988b] (figures 2 and 3) composed of seven coherent tectonostratigraphic terranes separated by low-
Figure 2. Franciscan Complex of the central San Francisco Bay area. Legend for figures 2 and 3 is on figure 3. All contacts shown are tectonic except the two east-west trending. Eocene contacts in the southwest part of the map. Map based on Wakabayashi (1989), Wakabayashi and Moores (1988a), Wahrhaftig (1984a, 1984b), Wahrhaftig and Wakabayashi (1989), Shervais (1989), Blake et al. (1984), Brabb and Pampeyan (1983), Blake et al. (1974), Schlocker (1974) and Bonilla (1971).
angle melange zones. Regional dips of the nappes are defined by exposures of melange matrix foliation and the bedding in the coherent nappes, that generally dips parallel to the foliation in the bounding melanges. The nappe stack is about 10 km thick, with dimensions of larger nappes of about 30 km across by 70 km along strike. The nappe stack is folded into a broad NW-trending synform centered on Tiburon Peninsula and a parallel antiform or faulted antiform centered on the eastern San Francisco Bay. Coherent strata and melange matrix foliation SW of the axis of Tiburon Peninsula, including the rocks in San Francisco, dip NE, whereas those NE of the axis dip to the SW. NE of the regional synformal axis is Red Rock, an island composed of chert and basalt of the Marin Headlands terrane. The strata at Red Rock dip to the SW (M. C. Blake, Jr. oral comm. 1986), placing them structurally below the exposures on the NE side of Tiburon Peninsula. The sandstones at Point Richmond, correlated in this study to rocks at San Bruno Mountain, dip to the SW, placing them structurally below the Marin Headlands terrane rocks at Red Rock. The structural stacking order from the NE side Tiburon Peninsula to Point Richmond is thus the same as that SW of the Tiburon Peninsula. East of the Point Richmond exposures, separated by an alluvium-covered area, coherent strata and melange matrix foliation dip uniformly to the NE, repeating the same structural stacking order, although many of the units are thinner than their correlatives SW of the major synclinal axis.

Among the features of the nappe stack are:
(1) Over 99% of the high-grade blocks in this section are present in the Tiburon melange that occupies the highest Franciscan structural horizon [Wakabayashi 1989]. Most of the other high-grade blocks reside in melanges separating coherent nappes. (2) Coherent blueschists of the Angel Island nappe, possibly correlative to the Pickett Peak or Yolla Bolly terranes of the northern Coast Ranges, make up the structurally highest Franciscan coherent unit in the nappe stack. [3] Coherent nappes appear to be internally imbricated [Blake et al. 1984; Wahrhaftig 1984a; Larue et al. 1989]. (4) The largest melange zones (200–1500 m thick) are those separating the coherent nappes. Minor melanges (up to 300 m thick) are present as part of the internal imbrication of coherent nappes, partic-
ularly in the Permanente and Marin Headlands terranes. (5) The Permanente terrane, separated by the San Andreas fault from the rest of the nappes, is correlated to a structural level somewhere below the Marin Headlands terrane, and probably the San Bruno Mountain nappe, based on field relations south of the line of section where the Permanente terrane crops out on the east side of the San Andreas fault.

Accretionary ages of nappes can be estimated from several types of data: (1) The age of overlap assemblages combined with the ages of the youngest strata in the overlapped terranes bracket the age of emplacement. (2) Metamorphic ages approximate the time of subduction and incorporation into the accretionary complex for metamorphosed terranes. (3) The fossil age of the youngest clastic strata in a terrane may approximate when a terrane approached the trench shortly before accretion. Controversy exists over whether or not some Franciscan clastic rocks were translated a large distance parallel to the plate margin after deposition and before incorporation into the Franciscan. Blake and Jones [1981] and Jayko and Blake [1984] proposed an exotic origin for Franciscan sandstones that differed in framework modes from coeval Great Valley sequence sandstones of similar age. Dickinson et al. [1982] suggested that differences in framework modes of coeval Great Valley and Franciscan sandstones may be due to complexities within the same arc-trench depositional system, and that all Franciscan sandstones were deposited near the site of accretion. Seiders [1988, 1991] and Seiders and Blome [1988] noted the similarity of coeval Great Valley sequence and Franciscan conglomerates and proposed that all Franciscan clastic rocks were deposited near the site of accretion. In the Bay area, only the Alcatraz terrane sandstones differ greatly in framework modes from coeval Great Valley sequence sandstones (Jayko and Blake 1984). Thus, whether one accepts an exotic or local origin for the Alcatraz terrane sandstones, the fossil ages from the other sandstone units (Marin Headlands, Novato Quarry-San Bruno Mountain) may closely approximate the timing of accretion for these rocks. (4) The fossil age of limestones in the Permanente terrane, combined with the calculated paleolatitude of deposition and plate motion models, was used by Tarduno et al. [1985] to estimate the accretion age of this unit. Estimated accretionary ages for the nappe units in the Bay area are listed in descending structural order as follows: (1) the Tiburon melange: 140–160 Ma based on the metamorphic age of the included blocks, interpreted in this structural horizon to be at their original structural level of accretion; (2) the Angel Island nappe: 130–150 Ma based on tentative correlations to similar rocks at Ward Creek and in the Pickett Peak terrane of the northern Coast Ranges that have yielded metamorphic ages in this age range; (3) the Alcatraz terrane: 135 Ma based on Valanginian fossils found in the unit (Blake et al. 1984); (4) the Marin Headlands terrane: 95 Ma based on Cenomanian fossils found in detrital rocks of the unit (Blake et al. 1984); (5) the San Bruno nappe: 75–85 Ma based on Campanian fossils in the Novato Quarry terrane (Blake et al. 1982), that is a part of this structural horizon in the eastern San Francisco Bay area; (6) the Permanente terrane: 65 Ma estimated by Tarduno et al. [1985] as described above; and (7) the Salinian block: 50–60 Ma based on the Paleocene fossil age of rocks involved in mylonitization at the Salinian-Franciscan contact and Eocene fossil age of underformed overlap strata (Wakabayashi and Moores 1988a). The progressive decrease in apparent emplacement ages toward lower structural levels in the Bay area suggests sequential off-scrapping or underplating in an accretionary complex as envisioned by Karig and Sharan [1975] (Wakabayashi and Moores 1988b). If the thrust sheets formed during the Cenozoic [e.g., Suppe 1978], such a sequence of structurally downward younging of apparent emplacement ages would be highly fortuitous.

The Cazadero region, also within the San Francisco block, may display more complex low-angle tectonic contacts [Gealey 1951; Bailey et al. 1964; Blake et al. 1971; Wakabayashi unpub. data] (figure 4). The regional low-angle nature of the contacts can be inferred on the basis of the sinuous trace of the contacts and repeated units in map view (figure 4). Based on crosscutting relationships, different generations of low-angle faults are present, some of which may post-date the accretion of the units. The younger faults may be similar to Cenozoic thrusts identified by Suppe [1978], and Phipps [1983, 1984a, 1984b] elsewhere in the northern Coast Ranges. If the younger faults are removed, the older low-angle fault contacts of the Cazadero region appear to form an accretionary age nappe stack similar to that of the Bay area, 5 km thick (excluding the thickness of the Coastal Belt), with larger nappe sheet dimensions of 45 km across and 70 km along strike. Similar to the San Francisco Bay area, probable nappe emplacement ages decrease structurally downward, with the following sequence: (1) Skaggs Springs schist: 145 Ma based on metamorphic age; (2) greenstone with incipient blueschist metamorphism of uncertain age; (3) melange of uncertain age; (4) the Rio Nido terrane: 90
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Franciscan rock units:
Tfcb: Coastal Belt: variably deformed sandstone and shale; prehnite pumpellyite grade and lower.
Kfr: Rio Nido terrane: variably deformed sandstone and shale; prehnite pumpellyite grade and lower, shown in light stipple.

KJfu: shale matrix melange; shown in dense stipple.
KJfg: greenstone; lacks fabric; incipient blueschist metamorphism.
KJms: Skaggs Springs schist; fine-grained blue amphibole-bearing schist.
KJmv: blueschist grade metabasalts of the Ward Creek area.
sp: serpentinite

Non-Franciscan rock units:
KJogv: Coast Range ophiolite and/or Great Valley Sequence.

Figure 4. Map and cross section of Franciscan Complex and related rocks in the Healdsburg region. All contacts are tectonic. Map derived from Blake et al. (1971, 1984), Erikson (unpub. data), and Wakabayashi (unpub. data). Note several different generations of thrust faults on the cross section.
Ma based on Turonian fossils; (5) the Coastal Belt (structurally highest part): <60 Ma based on fossils in detrital rocks.

In Franciscan exposures in the northern Coast Ranges composed mainly of melange, Kleist (1974), Gucwa (1975), and Jordan (1978) differentiated distinct structural horizons. Scarce age data from these units suggest that they may represent a downward-younging sequence (Maxwell 1974), with the following age constraints: (1) Bald Peak schist: 110–146 + Ma based on metamorphic age [Suppe and Armstrong 1972; Lanphere et al. 1978; McDowell et al. 1984] (probably closer to the older part of the age range, see later discussion of metamorphism); (2) Poison Rocks melange: 130–150 Ma based on fossils from the shale matrix [Jordan 1978]; (3) Elk Creek melange: 90–110 Ma based on microfossils in limestone concretions within shale of the melange matrix (Gucwa 1975); (4) Tin Creek melange: no age constraint; (5) Eel River melange: 90–110 Ma, based on microfossils in limestone concretions within shale of the melange matrix (Gucwa 1975); (6) Laytonville melange: probably ≤80 Ma, based on the Albian-Cenomanian age of the youngest beds in limestone blocks and the suggestion that these blocks probably traveled some distance after pelagic deposition to the site of accretion [e.g., Alvarez et al. 1980]; and (7) Coastal Belt: <60 Ma based on the fossil age of detrital sedimentary rocks [Blake et al. 1988]. Regional-scale thrust faults that formed during subduction have been identified in the Eastern Belt of the northern Coast Ranges [Worrall 1981; Jayko and Blake 1989], and analogous structures may exist in the Diablo Range [Cowan 1974]. In the Coastal Belt, the geometry of fault contacts are consistent with sequential offscraping and underplating of trench sediments at a subduction zone [Bachman 1978], with the exception of possible trench slope basin deposits [the Yager terrane of Underwood and Bachman 1985]. Seidens (1988, 1991) identified the same distinctive conglomerate suites in both the Franciscan and the coeval Great Valley sequence, with Franciscan conglomerates stacked upside-down compared to their Great Valley sequence counterparts, which were deposited as a normal stratigraphic sequence. Such a relationship is suggestive of sequential accretion of the Franciscan units [Seidens 1988, 1991]. Seidens (1991) utilized these Franciscan conglomerate horizons as stratigraphic or structural markers and demonstrated that this accretionary structure type is present over much of the northern Coast Ranges [Seidens 1991, figure 2].

The above examples illustrate that nappé structures that formed during subduction may be present throughout the Franciscan [interpreted nappé stacks, speculative correlations and accretionary age constraints are illustrated in Repository File, figures A and B]. These relationships suggest that Franciscan terranes represent components of an accretionary wedge formed by sequential offscraping and underplating, rather than a series of unrelated forearc slivers juxtaposed by strike-slip faulting.

Oblique Plate Convergence and Consequences for Franciscan Tectonics

Plate convergence during much of the Franciscan accretion may have been highly oblique [Engebretson et al. 1985]. Oblique plate convergence is consistent with the southerly latitude of formation of some Franciscan oceanic rock units [e.g., Alvarez et al. 1980; Tarduno et al. 1985]. At the Franciscan trench [western North American plate margin], convergence is calculated to have been oblique-sinistral prior to 118 Ma, nearly orthogonal from 118 to 100 Ma and from 56 Ma to the cessation of subduction, and oblique dextral from 100 to 56 Ma [Engebretson et al. 1985]. Comparatively large uncertainties in relative plate motions exist from 118 to 83 Ma, the period spanned by the Cretaceous normal superchron [Engebretson et al. 1985]. Oblique plate convergence is generally thought to be resolved into orthogonal subduction and trench-parallel strike-slip [e.g., Fitch 1972; Beck 1983]. Recent research suggests resolution of oblique convergence into oblique thrusting and trench-parallel strike-slip with about 60% of the trench-parallel component partitioned into strike-slip faulting [Ekström and Engdahl 1989].

Possible oblique subduction fabrics exist in the Skaggs Springs schist of the San Francisco block. The 70 × 3 km blueschist belt [figure 4] has a pervasive stretching lineation oriented sub-parallel to the length of the belt with a gentle E-SE plunge [Wakabayashi unpub. data]. Glaucophane is aligned with long axes parallel to this lineation, and lawsonite overgrows a later stage of folding that locally folds the lineation. Thus both the lineation and a subsequent deformational episode formed in blueschist facies conditions. The lineation trend is independent of the steepness of foliation dip, indicating that the lineation has not been rotated to near parallelism with the belt axis by later folding. Shear sense indicators and the lineation trend and plunge suggest W-NW-directed oblique thrusting or sinistral strike-slip [Wakabay-
ashi unpub. data). Based on the above it is concluded that the fabric in the Skaggs Springs schist may have resulted from sinistral-oblique subduction. The 143 Ma metamorphic age of this unit (Wakabayashi and Deino 1989) is within the calculated period of sinistral-oblique convergence at the Franciscan trench (Engebretson et al. 1985). Sinistral-oblique convergence during this period is also in agreement with the sense of shearing of similar age noted in the Galice Formation and the basal thrust of the Josephine ophiolite, units situated inboard (east) of the Franciscan in southwestern Oregon (Harper et al. 1990). Other oblique subduction fabrics (including dextral fabrics) have not yet been recognized in the Franciscan, possibly in part because of the extremely fine-grained nature of metamorphic minerals in most Franciscan coherent blueschists (much finer than the Skaggs Springs schist).

Depending on how much of the trench-parallel plate motion was partitioned into oblique subduction/thrusting, a large magnitude of strike-slip displacement (hundreds of km) may have been accommodated inboard of the Franciscan trench. The magnitude of tangential plate movement at the Franciscan trench need not be as great as the latitudinal shift suggested by paleomagnetic data from some of the Franciscan oceanic terranes. This is because of the differences in location of the terrane during transit on the oceanic plate and the location of the Franciscan trench relative to the pole(s) of rotation between North America and the oceanic plate(s), and the possibility of additional plate boundaries. In addition, evidence for compaction flattening of magnetic inclinations in deep sea sediments suggests that the paleomagnetic data from the oceanic rocks may overestimate the magnitude of latitudinal transport (Tarduno 1990). Plate motion models of Engebretson et al. (1985) suggest about 2400 km of sinistral trench-parallel relative plate motion at the Franciscan trench during the period from 163 to 118 Ma, and about 2400 km of dextral relative motion from 100 to 56 Ma. Relatively small magnitudes of trench-parallel motion are calculated for the period between 118 and 100 Ma and the period between 56 Ma and the cessation of subduction (Engebretson et al. 1985). Note, as mentioned previously, the large uncertainties for the period from 118 to 83 Ma. If the 60% partitioning estimate of Ekström and Engdahl (1989) is adopted for a first approximation, then the magnitude of trench-parallel motion accommodated by strike-slip faulting may have been about 1400 km of sinistral faulting from 163 to 118 Ma, with a like amount of dextral faulting from 100 to 56 Ma. The Franciscan Central Belt has been suggested as a zone of large magnitude strike-slip during the period of oblique convergence (e.g., McLaughlin and Ohlin 1984; McLaughlin et al. 1988; Blake et al. 1988). Several lines of field evidence argue against large magnitude (>500 km or so) strike-slip within the Franciscan: [1] The preservation of apparent accretionary sequences involving most or all of the Franciscan is inconsistent with dissection of the accretionary wedge by strike-slip faults of large displacement. [2] Conglomerate suites show little evidence of large scale strike-slip displacement within the Franciscan (Seiders 1991). [3] Vitrinite reflectance data (Underwood et al. 1988; Blake et al. 1988) indicate a west-to-east gradient of increasing metamorphic temperature across Central and Eastern Belts of the northern Coast Ranges that suggests no major (hundreds to thousands of km) post-metamorphic discontinuities. Distributed strike-slip faulting with <100 km of aggregate displacement, and less than ~20 km of displacement per fault, during subduction can probably be accommodated by the above relationships. Examples of such faulting may include Paleocene-Eocene faulting suggested by Blake et al. (1985) and McLaughlin et al. (1988).

If strike-slip faulting of large displacement took place during subduction, the faults must have been located inboard (east) of the Franciscan, possibly in the vicinity of the coeval magmatic arc, analogous to modern examples of obliquely convergent arc-trench systems such as the Indonesian region (e.g., Fitch 1972) and the Aleutians (e.g., Ekström and Engdahl 1989). Although few studies of syn-subduction strike-slip faulting east of the Franciscan Complex have been conducted, several examples of such faults and related deformation may have been identified: [1] evidence for 400–500 km of dextral slip that took place between approximately 150 Ma and 90 Ma along the east margin of the Sierra Nevada (Lahren and Schweickert 1989; Lahren et al. 1990; interpreted age of movement slightly modified by evaluation of Sierra plutonic ages); [2] the 85–100 Ma proto-Kern Canyon fault within the Sierra Nevada batholith, with an estimated 40 or more km of dextral slip (Busby-Spera and Saleeby 1990); [3] regional ductile deformation of 151–123 Ma age with sinistral-oblique sense of shear in the western Sierra Nevada (Paterson et al. 1987; Tobisch et al. 1989); [4] accommodation of a large amount of arc-parallel displacement (hundreds of kilometers) within the Sierra Nevada batholith by emplacement of the plutons in a transtensional environment (Saleeby 1991), and [5] the Pine Nut fault system of western Nevada,
with an undetermined amount of left slip from 155 Ma to the Late Cretaceous and right slip of uncertain magnitude thereafter (Avé Lallemant and Oldow 1988).

Although plate convergence was at times highly oblique, Franciscan subduction was probably continuous during the 140 m.y. of the assembly of the complex (although accretion need not have been), because cessation of subduction (with or without conversion to a transform fault boundary) would have resulted in thermal overprinting of high P/T rocks (Cloos and Dumitru 1987) and raised geothermal gradients in the Great Valley sequence (Dumitru 1988), which are not recognized (Dumitru 1988; Ernst 1988). Continuous subduction is consistent with the continuity of U/Pb zircon ages for plutons of the coeval Sierra Nevada arc and arc volcanism east of the Sierra Nevada (combined data of: Stern et al. 1981; Chen and Moore 1982; Tobisch et al. 1986; Hanson et al. 1987; Sharp 1989; Saleeby et al. 1989a, 1989b).

Franciscan Accretionary Details: Small Total Volume and Along Strike Variation

The Franciscan accretionary wedge, particularly the Eastern and Central belts, comprises a small volume of material compared to some modern accretionary prisms that formed over a shorter time period (e.g., Indonesia, Hamilton 1979; Aleutians, Moore et al. 1991; parts of Cascadia, Davis and Hyndman 1989). Based on the lack of intra-Franciscan strike-slip faulting noted above, strike-slip truncation probably did not cause the reduced accretionary prism volume. A process for reducing accreted volume more consistent with Franciscan field relations is sediment subduction or subduction erosion (e.g., Scholl et al. 1980; von Huene 1986), whereby sediment is subducted without accretion and/or previously-accreted hanging wall material is removed by abrasion by the downgoing plate. In this respect, the Franciscan accretionary complex may be intermediate in character between complexes with voluminous sediment accretion noted above, and the Peru and Marianas margins, which have a history of prolonged subduction with little or no accretion (e.g., von Huene and Lallemant 1990; Hussong and Uyeda 1981).

Even if Neogene strike-slip faulting is accounted for, considerable along strike variable exists in the Franciscan. Among the most interesting variations is the large proportion of melange in the northern Coast Ranges compared to mostly coherent units in the Bay area, and the lack of an equivalent to the Pickett Peak terrane in the Diablo Range. The along strike variation of the Franciscan can be partly explained by the discontinuous nature of accretion along the trench, because the various accreted elements, such as seamounts, oceanic rises, and packets of trench sediment, did not extend the length of the trench. Some variation, such as the discontinuous nature of the Pickett Peak terrane schists and equivalents, may have also resulted from differences in location, orientation, and displacements of post-accretionary thrust and normal faults.

The Coastal Belt is not present in the Bay area or southern Coast Ranges. This may be because Salinian block emplacement (50–60 Ma, Wakabayashi and Moores 1988a) was taking place while early Coastal Belt accretion (40–60 Ma, Blake et al. 1988) was occurring to the north or because the older Coastal Belt rocks are offshore. Equivalents of younger Coastal Belt rocks are probably present offshore at the latitude of the Bay area and southern Coast Ranges (Page 1981).

Metamorphism and Its Importance in Franciscan Tectonic History

In addition to regional structural relations, metamorphism of Franciscan rocks is helpful in reconstructing tectonic history. A much-debated problem of Franciscan tectonics is the apparent gap in metamorphic age and difference in metamorphic grade between the high-grade blocks and the oldest coherent blueschists. These differences may suggest a pre-Franciscan origin for the high-grade blocks (e.g., Coleman and Lanphere 1971; Blake et al. 1984). Alternatively, high-grade blocks and coherent blueschists may be part of the same subduction event (e.g., Suppe and Poland 1978; Cloos 1985; Wakabayashi 1990). This problem is addressed using petrologic, geochronologic, and field data from high-grade blocks and coherent blueschists.

Many “high-grade” blueschist and eclogite blocks possess relict amphibolite mineralogy (Blake et al. 1984; Moore and Blake 1989). Many blocks are enclosed by, or display remnants of, an actinolite-rich rind that may have formed by metasomatic reaction between the blocks and surrounding serpentinite (Coleman and Lanphere 1971; Moore 1984). The rinds overprint some of the blueschist growth stages in the high-grade blocks (Moore 1984). Textural, petrologic, and geochronologic data indicate that high-grade blocks were initially metamorphosed under amphibolite facies conditions, then cooled through conditions of increasing P/T ratio to the blueschist facies, a “counterclock-
The age of initial amphibolite-grade high-grade block metamorphism is probably about 158–163 Ma, based on Ar/Ar plateau ages from hornblendes (Ross and Sharp 1986, 1988). Blueschist overprint ages are 158–162 Ma (blue amphibole Ar/Ar plateau ages, Ross and Sharp 1986), 162 Ma [U/Pb isochron, Mattinson 1986] and 139–150 Ma [white mica K/Ar and Ar/Ar, Coleman and Lanphere 1971; Suppe and Armstrong 1972, McDowell et al. 1984; Wakabayashi and Deino 1989]. Actinolite-bearing rinds that commonly enclose the blocks have yielded 157 and 159 Ma K-Ar dates [Coleman and Lanphere 1971, recalculated using decay constants of Steiger and Jäger 1977]. The blue amphibole, actinolite rind, and U/Pb ages, combined with a similar age range for hornblendes, suggest that the high-grade blocks may have evolved from amphibolites to blueschists within 5 m.y. or less.

Figure 5. A: Evolution of Franciscan metamorphism: P-T paths shown are for material subducted at about: (1) 160 Ma (two representative P-T paths for high-grade blocks shown), (2) 145 Ma [Ward Creek coherent blueschist], (3) 90 Ma [Diablo Range] and 65 Ma [Permanente terrane]. Note the drop in peak metamorphic temperatures with time with most of the decrease within the first 15 m.y. A steady-state subduction geotherm may have developed at or before 100 Ma. The cooling of the subduction complex is attributed to the dissipation of heat from the hanging wall of the subduction zone. gl: stability field of glaucophane from Maresch [1977]; ab = jd + q: albite = jadeite + quartz from Newton and Smith [1967]. Sources: [1] Wakabayashi [1990], [2] Maruyama and Liu [1988], [3] Maruyama et al. [1985], Larue et al. [1989]. B: Cartoons illustrating Franciscan metamorphic evolution. The cartoons depict the relative structural position of units subducted, underplated and metamorphosed at 160, 145, 90, and 65 Ma. Inset at top of figure is a schematic enlargement of the dynamothermal aureole formed during subduction initiation. The thickness of the aureole is greatly exaggerated. This inset illustrates the origin of the wide variation in peak metamorphic temperatures and pressures in Franciscan high-grade blocks [Wakabayashi 1990]. Temperature variation is influenced by rather small differences in distance from the hanging wall and pressure is influenced by depth of underplating in the subduction zone. Points [a] and [b] in the inset correspond to the two representative P-T paths for high-grade blocks shown in "A."
The younger white mica ages may reflect the lower blocking temperature of white mica relative to amphibole [e.g., compare Harrison 1981, for amphibole, and Wijbrans and McDougall 1988, for white mica] and suggest a variable cooling history for the blocks. Preservation of metamorphic assemblages intermediate in textural successions and P-T conditions between the early amphibolite and late blueschist assemblages, and geochronologic data, indicate that high P-T overprints over the early amphibolite assemblages resulted from continuous evolution in P-T conditions, rather than an overprinting of an unrelated, earlier metamorphic event [Wakabayashi 1990].

Franciscan coherent metamorphic rocks range in grade from blueschist-greenschist transition in the structurally highest Pickett Peak terrane and Ward Creek coherent blueschists [Brown and Ghent 1983; Maruyama and Liou 1988] to lawsonite blueschist in Yolla Bolly terrane [Blake et al. 1988] and Diablo Range [Ernst et al. 1970; Maruyama et al. 1985] metagreywackes. The prograde P-T path for the Pickett Peak terrane and Ward Creek coherent blueschist metamorphism was slightly clockwise [Brown and Ghent 1983; Maruyama and Liou 1988] (see figure 5). The fine-grained coherent blueschists [≤0.05 mm white mica is the principal K-bearing phase] of the Pickett Peak terrane have not allowed the extraction of mineral separates in most cases. Consequently, nearly all coherent blueschist ages have been whole rock K/Ar dates. The South Fork Mountain Schist of the Pickett Peak terrane has yielded whole rock K/Ar and whole rock total fusion Ar/Ar dates of about 110–146 Ma [Suppe and Armstrong 1972; Lanphere et al. 1978; McDowell et al. 1984]. An Ar/Ar white mica plateau age of 143 Ma has been obtained from the somewhat coarser-grained [white mica ≤0.4 mm in size] Ward Creek coherent blueschists [Wakabayashi and Deino 1989].

Lanphere et al. (1978) suggested that Pickett Peak terrane ages >125 Ma were caused by extraneous argon from detrital white mica and concluded that 115–125 Ma represented the true metamorphic age of the rocks. McDowell et al. (1984) noted, however, that the >125 Ma ages are from the most texturally reconstituted samples, that lack detrital white mica, and are therefore valid dates. The Ward Creek white mica Ar/Ar step heating date supports this conclusion. Given the temperature of metamorphism [up to 330–345°C, Blake et al. 1988], that is close to or exceeds the blocking temperature for Ar in white mica [e.g., Wijbrans and McDougall 1988], and susceptibility of the extremely fine-grained micas of these schists to post-metamorphic argon loss (during cooling or subsequent thermal disturbance) [e.g., Dodson 1973], even the oldest Pickett Peak terrane ages probably represent only minimum ages of metamorphism. Although the white micas of the coherent blueschists are much finer-grained than those of the high-grade blocks and are thus potentially less retentive of argon [e.g., Dodson 1973], the oldest coherent blueschist ages [135–146 Ma] still overlap the 139–159 Ma age range of high-grade block K/Ar and Ar/Ar white mica ages, suggesting no gap in metamorphic age.

Yolla Bolly terrane and Diablo Range rocks have yielded whole rock K/Ar dates of about 90–115 Ma [Suppe and Armstrong 1972]. Some Yolla Bolly terrane ages may be either too young [Ar loss from fine-grained white mica] or too old [premetamorphic Ar from detrital white mica [Blake et al. 1988]]. Blueschist metamorphism in part of the Yolla Bolly terrane occurred at least as recently as about 95 Ma, because blueschist grade metagreywacke in the Hull Mountain area of the northern Coast Ranges has yielded Cenomanian fossils [Blake et al. 1988]. Mattinson and Echeverria [1980] obtained a 92 Ma U-Pb isochron metamorphic age from a Diablo Range blueschist grade metagabbro.

A <74–85> Ma metamorphic age is suggested for part of the blueschist facies Burnt Hills terrane of the Diablo Range that has yielded Campanian fossils [M. C. Blake, Jr., oral comm. 1989]. Locally preserved blueschist facies metamorphism in the Permanente terrane of the Bay area [Larue et al. 1989], combined with the accretion age estimate of Tarduno et al. [1985], suggest a blueschist metamorphic age of about 65 Ma.

Based on the above data, the following age ranges are suggested for Franciscan metamorphism: [1] high-grade block amphibolite metamorphism: 163–158 Ma; [2] rapid cooling to blueschist conditions within 5 m.y. after amphibolite metamorphism and variable further cooling to below the blocking temperature for Ar in white mica from 159 to 139 Ma; and [3] coherent blueschist metamorphism: 146+ to 80 Ma or somewhat younger. Geochronologic and petrologic data suggest continuity in age and metamorphic conditions between high-grade blocks and coherent blueschists. It is thus likely that both high-grade blocks and coherent blueschists formed during Franciscan subduction. A model for the metamorphic evolution of the high-grade blocks is presented [Wakabayashi 1990], followed by a discussion of coherent blueschist evolution:

High-grade block precursors formed as amphibolites under the hot hanging wall of the just-
initiated Franciscan subduction zone and were subsequently underplated to the upper plate [Platt 1975; Suppe and Foland 1978; Cloos 1985]. With continued subduction, the hanging wall cooled, and the amphibolites were overprinted with assemblages of higher P/T ratio. The upper mantle wedge present above the zone of amphibolite formation in the subduction zone may have been the source for the serpentine matrix often found in close association with the blocks. The metamorphic ages of the block rinds are within the same range as amphibolite metamorphism in the blocks, suggesting that the blocks were in contact with ultramafic rocks during or shortly after metamorphism.

Thermal modeling by Hacker [1990] and Cloos [1985] suggest that rocks underplated immediately after, and just beneath, the high-temperature horizon of the high-grade blocks may have experienced a slightly clockwise prograde P-T path with lower peak temperatures than the high-grade blocks. These thermal models are consistent with the P-T paths determined for the Ward Creek coherent blueschists [figure 5] and Pickett Peak terrane (Maruyama and Liou 1988; Brown and Ghent 1983). Based on petrologic and geochronologic data, Franciscan coherent blueschists may represent a unit subducted after and underplated structurally below the accretionary horizon of the high-grade blocks. The structurally highest Pickett Peak terrane (and the correlative Ward Creek/Skaggs Springs blueschists) was accreted and metamorphosed first, followed by the Yolla Bolly terrane/Diablo Range. The trend of decreasing peak metamorphic temperatures and decreasing apparent geothermal gradient with decreasing age (figure 5) may be attributed to the continued dissipation of heat from the hot hanging wall of the subduction zone. Most of the temperature decrease occurred within the first 15 m.y. or less after subduction initiation, as predicted by thermal models [Cloos 1985; Peacock 1988].

Accretionary ages for some sub-blueschist grade units overlap ages of blueschist metamorphism [see also Repository figure B]. For example, while the prehnite-pumpellyite grade Marin Headlands terrane accreted in the Bay area in the Cenomanian, blueschist metamorphism took place in the Yolla Bolly terrane of northern Coast Ranges (Blake et al. 1988) and in the Diablo Range [Matinson and Echeverria 1980]. Presence or lack of blueschist metamorphism at the same time in different Franciscan regions may be a function of different depths of underplating or offscraping of correlative units along the Franciscan trench or simply an artifact of different levels of exposure of uplifted Franciscan units.

"Unconventional" Aspects of Franciscan Accretion: Distribution of High-Grade Blocks and "Tectonic Wedging"

Two aspects of Franciscan tectonics that may not fit a "conventional" model of accretion [such as Karig and Sharman 1975] are: [A] the distribution of high-grade blocks and [B] "tectonic wedging" expressed as east-vergent thrusting of the Franciscan Complex over the Great Valley sequence or Sierran basement [e.g., Wentworth et al. 1984].

A) High-grade blocks are found in melange zones other than the highest structural horizon in the Franciscan. Emplacement of these blocks at structurally lower levels requires mechanisms of tectonic and/or sedimentary recycling [Cloos 1986; Wakabayashi and Moores 1988b]. Some field relations relating to high-grade block distribution are: [a] Large concentrations of blocks occur in the structurally highest Franciscan horizon, just beneath Coast Range ophiolite or Great Valley sequence outliers. As interpreted in this paper, this horizon represents the original structural level of high-grade block accretion. [b] Blocks are common in shear zones and melange zones cutting or bounding coherent blueschist nappes, particularly the Skaggs Springs schist. These shear zones are generally narrow (<50 m) and commonly contain serpentine or metamorphosed ultramafic rocks. [c] Blocks are common in melanges at or near the contact between the Central Belt and Coastal Belt. [d] High-grade blocks rare in melanges within the Coastal Belt.


Some strengths and/or weaknesses of these mechanisms are summarized, numbered to correspond to the mechanism listed above: [1] Serpentine diapirism explains the common association of the blocks with serpentine, the common occurrence of blocks in narrow serpentine-filled shear zones that cut the foliation of the higher
grade coherent blueschists such as the Pickett Peak terrane and correlatives, especially the Skaggs Springs schist [Wakabayashi unpub. data] and Angel Island nappe [Wahrhaftig 1984b], and is consistent with the formation of the Mg-rich reaction rinds on the blocks. Association with serpentinite early in the history of the high-grade blocks is suggested by reaction rind ages that are close to the age of high-grade metamorphism in the blocks (Coleman and Lanphere 1971, see discussion in previous section), and possibly, the presence of serpentinite assemblages including antigorite and tremolite [nearly all of the serpentinite in the Franciscan and Coast Range ophiolite is composed of lower-grade chrysotile ± lizardite assemblages] associated with the blocks in the structurally highest melange in the San Francisco Bay area and in shear zones cutting the Skaggs Springs schist [Wakabayashi unpub. data] and Angel Island nappe [Wahrhaftig 1984b]. Serpentinite diapirism cannot account for common occurrences where blocks appear associated only with shale matrix in melanges (e.g., Cloos 1982). [2] Redeposition of high-grade blocks suggests prior uplift and erosion of high P-T rocks. Blueschist detritus is rare in Eastern and Central belt sandstones and conglomerates (e.g., Cowan and Page 1975). However, high-grade blocks represent a small enough volume of material that they may not have contributed a noticeable amount of blueschist detritus to Franciscan clastic rocks. Furthermore, high-grade blocks are present as blocks in basal Great Valley sequence olistostromes in the northern Coast Ranges (Phipps 1984b, Carlson 1981). [3,4] The lack of evidence for strike-slip faulting during subduction within the Franciscan argues against these mechanisms. (5) The melange return flow mechanism [e.g., Cloos 1984], including “intrusion” of melange between coherent units (suggested by Cloos 1984; field evidence presented in Becker and Cloos 1985; Cloos 1991), appears to explain high-grade block distribution fairly well.

In conclusion, field relations suggest that high-grade block distribution may have resulted from a combination of processes [1], [2], and [5], in the following sequence: [a] early association of blocks with serpentinite, [b] possible rapid upward movement of some blocks by entrainment in serpentinite diapirs and return flow of melange, [c] surface exposure and deposition of early uplifted blocks in olistostromes in both the Great Valley forearc basin and the Franciscan trench with resubduction of trench deposits, [d] continued emplacement and redistribution of blocks by melange flow and intrusion.

Aspects of block distribution not directly addressed by any of the mechanisms are the scarcity of blocks in Coastal Belt melanges and the high concentration of blocks in the vicinity of the Coastal Belt/Central Belt contact. A speculative explanation for this distribution pattern follows. The trench-parallel component of plate motion decreased sharply while the normal component increased somewhat from 75–56 Ma (Engebretson et al. 1985), coincident with the change from Central Belt to Coastal Belt accretion. Although return flow in obliquely subducting melanges has not been modeled, travel paths to and from the block source horizon should be longer than for trench-normal subduction. The change from highly oblique convergence to rapid normal convergence may have drastically shortened the return paths from the source horizon of blocks in melanges, resulting in a relatively high concentration of blocks at the Central Belt/Coastal Belt boundary melange. The change from Central Belt to Coastal Belt accretion also coincides with a relative increase in the volume of sediment accretion. The Coastal Belt, including offshore exposures, represents ≤50 m.y. of accretion but is comparable in volume to the adjacent Central and Eastern belts that accreted over a period of 100–110 m.y. The increase in volume of accreted sediment may have resulted from the overtopping of the forearc high, that had, up to this time, ponded much of the clastic sediment east of it in the Great Valley forearc basin (Ingersoll 1978). Increase in trench sediment volume may have caused underplating beneath the high-grade block horizon (compared to periodic accretion and tectonic erosion), sealing off the source horizon from further “plucking” by a flow melange and preventing emplacement of high-grade blocks into Coastal Belt melanges.

B) Tectonic wedging [e.g., Wentworth et al. 1984], characterized by the east-directed thrusting of Franciscan over presumed Sierran basement, is presently active along the eastern margin of the Coast Ranges [e.g., Wentworth et al. 1984; Namson and Davis 1988; Unruh and Moores 1990]. Related east-vergent thrusting in the Great Valley sequence may have initiated in the late Cretaceous based on structural evidence (Unruh and Moores 1990, 1992). This may have preceded or coincided with the initiation of east-directed thrusting of Franciscan over basement, constrained to be younger than the youngest blueschists in the upper plate (~75–90 Ma). Initiation of this thrusting may have resulted from one or a combination of the following: [1] shallowing of the dip of subduction from ~80 Ma (e.g., Dickinson and Snyder 1978); [2] an increase in convergence rate and/or greater
frontal accretion during the latest Cretaceous to early Tertiary (Engebretson et al. 1985; Ingersoll 1978), corresponding to the initiation of Coastal Belt accretion, that may have promoted increased thrust faulting to maintain a stable wedge geometry (e.g., Platt 1986); and (3) collision of buoyant material with the subduction zone (that may have caused the subduction shallowing in part). Such collisions during this time period may have involved aseismic ridges or seamount chains, such as the Permanente terrane at ~65 Ma (Henderson et al. 1984; Tarduno et al. 1985), or the continental Salinian block at 50–60 Ma (Wakabayashi and Moores 1988a). Accretion of the oceanic Nicason Reservoir, Geysers, and Marin Headlands terranes at ~95 Ma may have occurred too early for the initiation of east-directed thrusting but may have played a role in the shallowing of subduction dip. Clearly, much further study needs to be conducted to determine the timing and cause of the initiation of “tectonic wedging.”

**Franciscan Tectonic History: A Brief Summary**

Combining the available structural, metamorphic, and age data, the following Franciscan tectonic history is presented (see figure 6): Between about 163 and 169 Ma the Coast Range ophiolite formed [Hopson et al. 1981; Mattinson data cited in McLaughlin et al. 1988] in a back-arc basin over a west-dipping subduction zone [Moores 1970; Schweickert and Cowan 1975] (figure 6). The western North American continental margin chokes this subduction zone, and east-dipping subduction initiated to the west beneath the young Coast Range ophiolite from 163–158 Ma, trapping the ophiolite in a forearc setting relative to the new subduction zone. High-grade block precursors formed as amphibolites during the inception of subduction and were overprinted with higher P-T assemblages with cooling during continued subduction. The structurally highest coherent blueschists were underplated next at about 145+ Ma, followed by a series of accreted slices composed mostly of trench sediments with some materials rafted to the subduction zone on the down-going oceanic plate. Franciscan melanges formed as shear zones, both as part of the internal imbrication of coherent nappes and separating coherent nappes; and some of the melanges may represent material originally deposited as olistostromes in the trench prior to being subducted. Accreted units did not extend the full length of the trench, resulting in along-strike variation of the Franciscan. Depending on the depth at which the materials were off-scraped or underplated, some experienced high P-T metamorphism. The depth of accretion coupled with subsequent differential uplift and exposure controlled the distribution of exposed high P-T metamorphism in Franciscan rocks. Contemporary with Franciscan subduction was arc volcanism in the Sierra Nevada arc and forearc basin sedimentation in the Great Valley sequence to the east of the Franciscan. Oblique plate convergence may have resulted in latitudinal displacement of some accreted oceanic terranes, but not of trench-deposited detrital sedimentary rocks. Convergence was sinistral-oblique prior to 100 Ma and dextral-oblique thereafter [Engebretson et al. 1985]. Part of the trench-parallel component of relative plate
motion was partitioned into oblique thrusting with the remainder accommodated by strike-slip faults inboard of the Franciscan in the region of the magmatic arc. The magnitude of associated strike-slip faulting may have been about 1400 km sinistral strike-slip from 163–100 Ma, with the same amount of dextral strike-slip from 100 Ma to the termination of subduction, based on the plate motion calculations [Engebretson et al. 1985] and 60% partitioning of trench-parallel plate motion into strike-slip faulting [Ekström and Engdahl 1989]. East-directed thrusting of the Franciscan over the forearc basin and basement may have initiated some time after about 75 Ma with activity continuing to the present. From about 15 Ma, depending on latitude, the Mendocino triple junction migrated northward, and subduction was replaced by a strike-slip dominated tectonic regime [Page and Engebretson 1984]. Faulting and deformation associated with this transform regime disrupted the original structural relations in the Franciscan, severely overprinting the older structures.

ACKNOWLEDGMENTS

An early version of this paper appeared in an unpublished field trip guide, "Field Trip to the Napa-Sonoma Wine Region," distributed for a field trip for the 1990 AAPG meeting. The author's knowledge of the Franciscan has benefited from discussions and exchange of data from many individuals, particularly M. C. Blake, Jr., C. Wahrhaftig, V. M. Seiders, E. M. Moores, S. P. Phipps, W. G. Ernst, and M. Cloos. I thank The Journal of Geology reviewers for thorough, constructive reviews and R. C. Newton for helpful editorial comments.

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