

# Tectonic wedging, blueschist metamorphism, and exposure of blueschists: Are they compatible?

John Wakabayashi 1329 Sheridan Lane, Hayward, California 94544

Jeffrey R. Unruh William Lettis & Associates, 1000 Broadway, Suite 612, Oakland, California 94607

## ABSTRACT

Tectonic wedging is currently deforming rocks along the western margin of the Central Valley of California. Structural relations in the strata of the Mesozoic Great Valley Group fore-arc basin indicate that earlier phases of wedging were coeval with subduction and accretion of the Franciscan Complex to the west. The present-day geometry of tectonic wedging is incompatible with blueschist metamorphism in the Franciscan complex because the detachment for the wedge system would have prevented the transport of accretionary-wedge materials to great depth. We propose a sequence of tectonic events that reconciles these tectonic processes. Franciscan subduction and metamorphism began at ~165 Ma, and Great Valley Group deposition began in the Tithonian. Shortening affected Great Valley Group rocks in the Hauterivian-Barremian and may have coincided with a gap in blueschist metamorphism in the Franciscan. Major uplift of Franciscan blueschist relative to the unmetamorphosed Great Valley Group rocks began in the Albian-Cenomanian. This uplift was accommodated along an east-dipping extensional fault system between the Franciscan Complex and the structurally overlying Coast Range ophiolite and Great Valley Group. Movement on this fault system caused the western side of the fore-arc basin to subside, resulting in uninterrupted deposition of Great Valley Group sediments from the Cenomanian to the Campanian-Maastrichtian. The youngest exposed blueschists in the Franciscan were metamorphosed at 80–90 Ma. Uplift of blueschist relative to Great Valley Group rocks must have been complete prior to development of the present style of east-vergent tectonic wedging. This style of deformation probably began between the Maastrichtian and Paleocene, resulting in exhumation and deformation of both Franciscan and Great Valley Group rocks. The development of wedging was coincident in part with the shallowing of subduction dip and voluminous frontal accretion of the coastal belt of the Franciscan.

## INTRODUCTION

Recent studies show that tectonic wedging associated with east-vergent contraction is currently active and has deformed rocks along the western margin of the Central Valley in California (Wentworth and Zoback, 1989; Unruh and Moores, 1992; Fig. 1). The structural geometry can be generalized as an east-directed underthrust wedge, bounded below by a west-dipping detachment and above by east-dipping back thrusts. Structural relations in rocks older than late Cenozoic indicate that wedging may have been active during earlier time periods when the plate margin was a subduction zone (Wentworth et al., 1984; Fuis and Mooney, 1990; Unruh et al., 1993). This earlier deformation imbricated the unmetamorphosed fore-arc basin strata of the Great Valley Group as the accretionary wedge of the Franciscan Complex formed to the west (Unruh et al., 1991). This tectonic style has been compared to the modern Western Antilles and has been called a “two-sided” orogen (Unruh et al., 1991).

Coeval blueschist metamorphism in the subduction zone and east-vergent thrusting that places subduction-complex rocks over fore-arc basin strata as part of the wedging process presents a major problem (Fuis and Mooney, 1990; Wakabayashi, 1992). With the proposed wedge geometry, it is difficult to envision how

blueschist metamorphism of subduction-complex rocks that are now exposed could have taken place, because the detachment of the wedge system roots in the subduction zone and prevents accretionary-wedge material from reaching sufficient depth for high-pressure, low-temperature metamorphism. The kinematics and geometry of wedging proposed for the Franciscan appear to preclude simultaneous wedging and blueschist metamorphism; thus, the relative timing of these two processes remains a critical unresolved problem.

In this paper we attempt to resolve the relative timing of wedging and blueschist metamorphism and present reasonable geometries of trench and fore-arc deformation that are compatible with present-day field relations. We interpret Franciscan–Great Valley Group tectonic history with a sequence of schematic, kinematically restorable cross sections (Fig. 2). Seiders (1988) and Wakabayashi (1992) have suggested that Franciscan and Great Valley Group field relations preclude the large-scale (hundreds to thousands of kilometres) pre-Neogene strike-slip faulting advocated by other models (e.g., Blake et al., 1988). Regardless of the presence or absence of pre-Neogene strike-slip faulting, however, the schematic cross sections still represent a valid generalization of the trench-normal component of the deformational history. The cross sections are drawn

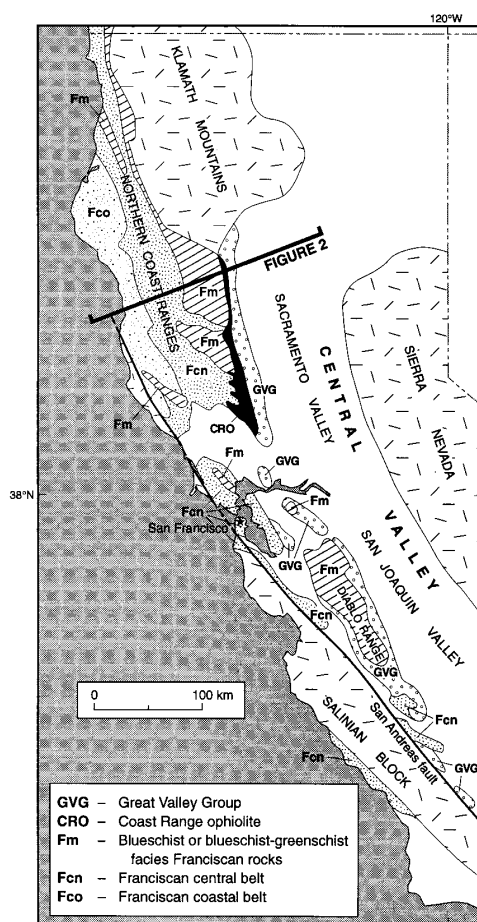
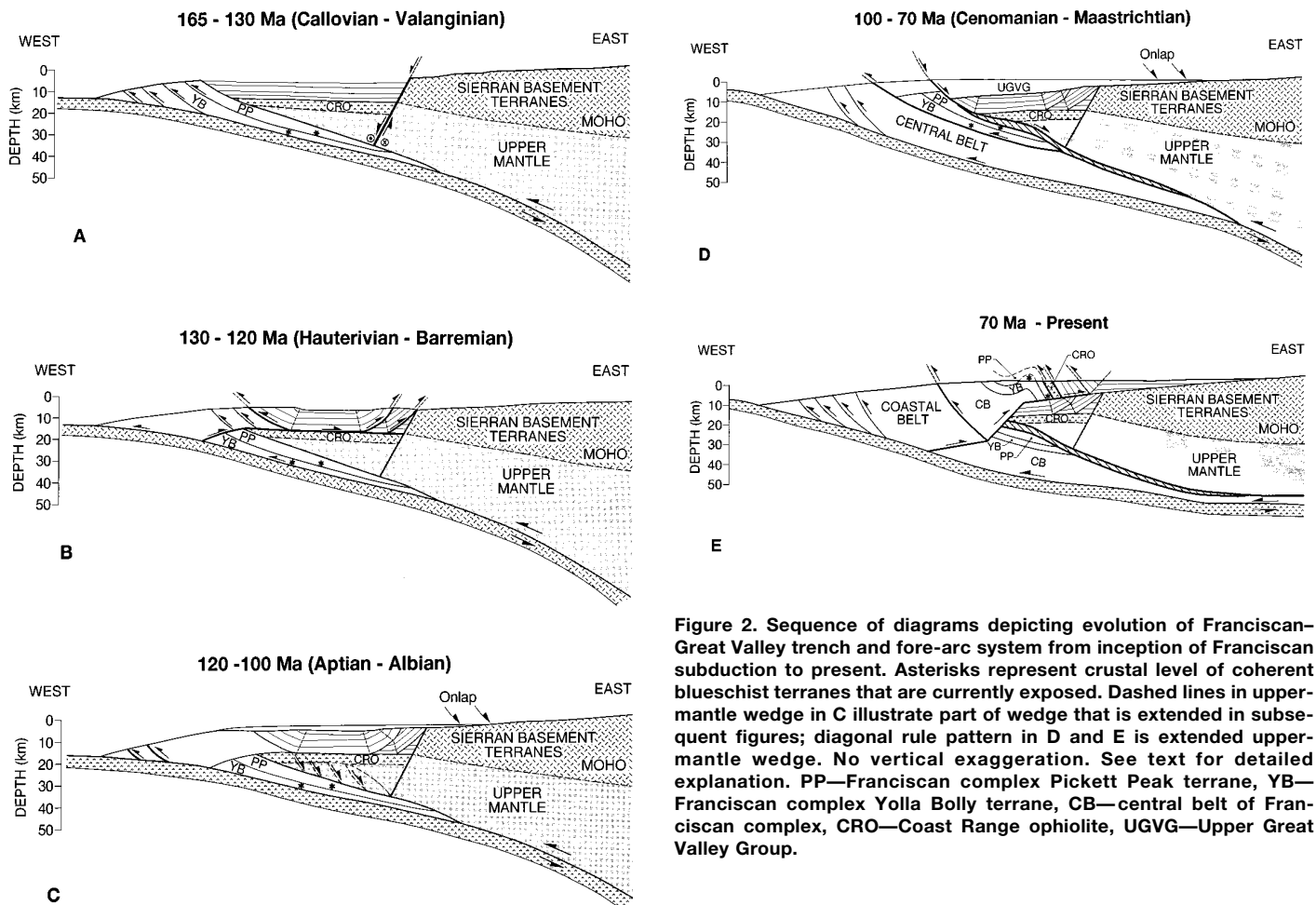


Figure 1. General distribution of Great Valley Group and Franciscan Complex rocks. Adapted from Wakabayashi (1992).



**Figure 2.** Sequence of diagrams depicting evolution of Franciscan-Great Valley trench and fore-arc system from inception of Franciscan subduction to present. Asterisks represent crustal level of coherent blueschist terranes that are currently exposed. Dashed lines in upper-mantle wedge in C illustrate part of wedge that is extended in subsequent figures; diagonal rule pattern in D and E is extended upper-mantle wedge. No vertical exaggeration. See text for detailed explanation. PP—Franciscan complex Pickett Peak terrane, YB—Franciscan complex Yolla Bolly terrane, CB—central belt of Franciscan complex, CRO—Coast Range ophiolite, UGVG—Upper Great Valley Group.

at the latitude of Maxwell's (1974) transect of the northern Coast Ranges, with approximate restoration of late Cenozoic strike-slip faulting. Significant along-strike variation is present in the Great Valley Group (Moxon, 1988) and in the Franciscan (Wakabayashi, 1992), and so the interpreted timing and kinematics should be considered generalizations. Subduction at the Franciscan trench was continuous from the inception of subduction at ~165 Ma to the passage of the Mendocino triple junction at ~10 Ma or later, depending on latitude (Wakabayashi, 1992).

## SEQUENCE OF TECTONIC EVENTS

### 165 to 130 Ma

East-dipping Franciscan subduction began at ~165 Ma, resulting in high-temperature metamorphism of the precursors to the Franciscan high-grade tectonic blocks as part of a subophiolitic sole, and was followed shortly by accretion and metamorphism of the oldest coherent blueschists, the Pickett Peak terrane, as the hanging-wall thermal anomaly dissipated (Wakabayashi, 1992). Isotopic ages indicate that the Pickett Peak terrane and equivalents were probably metamorphosed at or a little before 143 Ma (see Wakabayashi, 1992, for review of Franciscan isotopic ages). Accretion and blueschist facies metamorphism of the Yolla Bolly terrane structurally beneath the Pickett Peak terrane (Fig. 2A) may have begun at ~135 Ma, on the basis of fossil ages in sandstones (Murchev and Blake, 1993; Isozaki and Blake, 1994). Whole-rock K/Ar ages from the Yolla Bolly terrane range from ~90 to ~105 Ma (Suppe and Armstrong, 1972) and may be influenced by postmetamorphic Ar loss (Wakabayashi, 1992). The Pickett Peak and Yolla Bolly terranes both underwent high-pressure, low-temperature met-

amorphism at depths of  $\geq 25$ –30 km (Blake et al., 1988; Brown and Ghent, 1983; Ernst, 1993).

The oldest Great Valley Group strata (Tithonian) were deposited on oceanic crust of the Coast Range ophiolite, coincident with the early stages of Franciscan subduction (Dickinson and Seely, 1979) (Fig. 2A). Field evidence from the Sacramento Valley indicates uninterrupted deposition in the fore-arc basin from the Tithonian to the Valanginian-Hauterivian in an asymmetric basin that deepened to the east (Moxon, 1988). This eastern margin of the basin may have comprised a series of en echelon, left-stepping normal or oblique faults along a sinistral strike-slip fault system (Moxon, 1988). The strike-slip fault system may have formed as a consequence of strain partitioning of sinistral-oblique subduction (Wakabayashi, 1992).

### 130 to 120 Ma (Hauterivian-Barremian)

During this period, significant contractional deformation associated with east-vergent thrust faulting affected Great Valley Group strata (Unruh et al., 1993, 1995) (Fig. 2B). A major unconformity corresponding to deformation and erosion at this time is present in Great Valley Group exposures in the Sacramento Valley and most of the San Joaquin Valley. The most profound unconformity is in the San Joaquin Valley exposures (Moxon, 1988). East-vergent thrusts that deform the lower Great Valley Group section are interpreted from seismic reflection data (Unruh et al., 1993, 1995). In the Great Valley Group of the southernmost San Joaquin Valley, contractional deformation occurred 10 m.y. earlier than in other parts of the exposed fore-arc basin (Moxon, 1988). On the basis of the east-vergent geometry of the thrust faults, the detachment for

this deformation rooted in the subduction zone to the west. Such a geometry of thrusting should have interrupted deep underplating and blueschist metamorphism in the Franciscan (Fig. 2B). The absence of fossils of this age range (Hauterivian-Barremian) from blueschist-facies metagraywackes is consistent with this model. This period of deformation coincides with Early Cretaceous contraction in the Sevier belt to the east in the Great Basin (Allmendinger, 1992).

### 120 to 100 Ma (Aptian-Albian)

Contractional deformation in the Great Valley basin ceased during this period, and fore-arc basin sediments were deposited unconformably on deformed lower Great Valley Group strata (Fig. 2C) (Moxon, 1988; Unruh et al., 1995).

### 100 to 70 Ma (Cenomanian-Maastrichtian)

This time period encompassed the accretion of most of the oceanic terranes of the Franciscan Complex, such as the Marin Headlands, Geysers, Nicasio Reservoir, and Permanente terranes (Fig. 2D), most of which were accreted from 100 to 90 Ma (Murchey and Blake, 1993). Some of the currently exposed blueschists were metamorphosed during this period. The youngest blueschist facies rocks exposed at the approximate latitude of our transect are the metagraywackes of the Hull Mountain area that may have been metamorphosed at ~95 Ma, on the basis of Cenomanian fossils (Blake et al., 1988). Younger blueschist-grade metagraywackes of the Burnt Hills terrane in the Diablo Range 200 km south of our transect may have been metamorphosed at ~85 Ma on the basis of Santonian-Campanian fossils (Elder and Miller, 1990). Continuous deposition of the upper Great Valley Group fore-arc basin strata of Cenomanian to Campanian-Santonian age occurred in an asymmetric basin that deepened to the west (Moxon, 1988). Zircon fission-track data suggest uplift of ~20 km for the deeper parts of the Franciscan complex at 80–100 Ma (T. Tagami and T. A. Dumitru, 1994, written commun.; Dumitru and Tagami, 1991), consistent with major exhumation of blueschist terranes at this time.

The difference in crustal depth represented by the coherent blueschists and structurally overlying Coast Range ophiolite and Great Valley Group is 15–25 km (Platt, 1986). At the time of metamorphism of the blueschists, a thick wedge of upper-mantle lithosphere should have been present between the blueschists and the ophiolite (Fig. 2A). The differential uplift of the blueschists was accommodated by east-down normal faulting of the Coast Range ophiolite relative to the Franciscan (Platt, 1986; Jayko et al., 1987). This extensional deformation may not have had a symmetric core-complex configuration (with west- as well as east-dipping faults) as envisaged previously (Platt, 1986; Jayko et al., 1987). In most parts of the Franciscan where low-angle contacts are preserved, blueschists are structurally overlain by ophiolite or the Great Valley Group and underlain by comparatively low grade Franciscan rocks in an east-dipping tectonic stack (Worrall, 1981; Wakabayashi, 1992). These relations show that the blueschist was thrust westward over the lower-grade Franciscan terranes as these terranes were accreted. Little evidence exists for large-scale extension within the Great Valley Group, as proposed by Harms et al. (1992). Extension, therefore, appears to have been accommodated almost exclusively along the east-dipping contact between the Franciscan and the ophiolite (i.e., the Coast Range fault) with considerable attenuation of the upper-mantle wedge overlying the blueschists (Fig. 2D). This extension was coincident with, and accommodated in part by, subsidence along the western margin of the fore-arc basin that accompanied uninterrupted deposition of Great Valley Group strata.

Platt (1986) proposed that deep-seated extension of the subduction complex was driven by gravitational instability of the ac-

cretionary wedge (Platt, 1986). As previously noted, nearly all of the oceanic terranes of the Franciscan accreted during this period. Oceanic terranes, because of their greater coupling to the downgoing plate, would be expected to be preferentially underplated at greater depth than trench sediments, increasing wedge taper and promoting extension (Platt, 1986).

The missing crustal section between the ophiolite and blueschists also can be explained by out-of-sequence thrusting (such as deep-seated east-vergent thrusting followed by west-vergent thrusting, as suggested by Ring and Brandon, 1994). However, such a model requires the erosion of all crustal material above the blueschists (Ring and Brandon, 1994) and should have resulted in the exposure of ~100 000 km<sup>3</sup> (volume) of ultramafic material (the denuded upper-mantle wedge). The composition of Great Valley Group and Franciscan Complex sandstones and conglomerates of this and younger ages does not reflect a large influx of ultramafic material and thus does not support large-scale erosion to expose the blueschists. In addition, the thrust model predicts that thrusting should be associated with major shortening and erosion in the Great Valley Group. However, the inferred period of exhumation from zircon fission-track data, 100–80 Ma, is associated with continuous deposition in the Great Valley Group.

As reviewed above, younger blueschists (85–100 Ma) continued to form as the older blueschists such as the Yolla Bolly and Pickett Peak terranes were being exhumed. The blueschists should have reached the crustal level of the Great Valley Group by 60–70 Ma because the kinematics of deformation after 60–70 Ma are incompatible with relative uplift, as discussed below. Although significant uplift of blueschists relative to the Great Valley Group and Coast Range ophiolite took place from 100 to 70 Ma, sandstone compositions of the Franciscan complex and Great Valley Group indicate that widespread exposure of blueschists did not occur; we interpret the blueschists to have merely attained the crustal level of the lower Great Valley Group (Fig. 2D).

The rate of uplift of the blueschists relative to the Coast Range ophiolite during this time period was ~0.4 to ~1.0 mm/yr based on the inferred timing of the beginning of relative uplift, the ages of the youngest exposed blueschists, and the probable cessation of major relative uplift at 60–70 Ma.

### 70 Ma to Present

Major shortening in the Great Valley Group began in the latest Maastrichtian–early Paleocene (60–70 Ma) (Fig. 2E). This contractional deformation is recorded by major unconformities in these strata (Moxon, 1988) and is coincident with the beginning of the accretion of the coastal belt of the Franciscan. On the basis of proprietary seismic reflection data, and shallow subsurface and surface structural relations (Moxon, 1988), we interpret this deformation to represent the onset of the tectonic wedging that has continued episodically throughout the Cenozoic. The detachment for this deformation dipped west and rooted in the subduction zone. The Franciscan complex was thrust eastward over itself, the Coast Range ophiolite, and lower Great Valley Group. The upper plate of the thrust system was deformed by a series of east-dipping back thrusts, forming the tectonic-wedge geometry. The back thrusting locally reactivated the former extensional ophiolite-Franciscan contact (Namson and Davis, 1988; Phipps, 1984), producing west-vergent kinematic fabrics along the Coast Range fault (Ring and Brandon, 1994) and overprinting earlier fabrics. The detachment for the wedge system is currently at considerable depth in the Coast Ranges ( $\geq 15$  km) on the basis of seismic reflection and refraction data (e.g., Fuis and Mooney, 1990; Wentworth et al., 1984; Unruh et al., 1995). Thus, only the upper-plate rocks of this thrust system are now exposed on Earth's surface. Because of the geometry and kinematics

of tectonic wedging, significant uplift of blueschists *relative to Great Valley Group rocks* is not likely to occur in the hanging wall of the thrust system. Consequently, uplift of blueschists relative to the Coast Range ophiolite and the Great Valley Group must have been complete prior to the beginning of tectonic wedging at 60–70 Ma. Uplift of blueschist, ophiolite, and the Great Valley Group together *relative to Earth's surface* took place from 70 Ma to the present (Fig. 2E). Apatite fission-track data indicate uplift of both the Franciscan and Great Valley Group during this period (Dumitru, 1988, 1989). This uplift resulted in widespread exposure of blueschists by the mid-Tertiary (Cloos, 1986). The major tectonic transition in the fore arc coincided with two tectonic events:

1. The shallow slab subduction may have taken place at this time, coincident with the onset of Laramide deformation and cessation of Sierran plutonism inland (Dickinson and Snyder, 1978). This low-angle subduction may have increased coupling in the fore-arc area, promoting arcward-vergent contraction of the Great Valley basin.

2. Accretion of the Franciscan coastal belt took place at this time, representing the largest volume of frontally accreted material in the Franciscan. The offscraping of this unit would have decreased the wedge taper and perhaps triggered shortening in the wedge (Platt, 1986).

With some interruptions, tectonic wedging has continued to the present and is currently active in a transpressional-transform plate boundary rather than a subduction-complex tectonic setting.

#### ACKNOWLEDGMENTS

We thank D. Cowan and M. Brandon for thorough reviews of the manuscript.

#### REFERENCES CITED

- Allmendinger, R. W., 1992, Fold and thrust tectonics of the western United States exclusive of the accreted terranes, *in* Burchfiel, B. C., et al., eds., *The Cordilleran orogen: Conterminous U.S.*: Boulder, Colorado, Geological Society of America, *Geology of North America*, v. G-3, p. 583–607.
- Blake, M. C., Jr., Jayko, A. S., McLaughlin, R. J., and Underwood, M. B., 1988, Metamorphic and tectonic evolution of the Franciscan Complex, northern California, *in* Ernst, W. G., ed., *Rubey Volume VII: Englewood Cliffs, New Jersey*, Prentice-Hall, p. 1035–1060.
- Brown, E. H., and Ghent, E. D., 1983, Mineralogy and phase relations in the blueschist facies of the Black Butte and Ball Rock areas, northern California Coast Ranges: *American Mineralogist*, v. 68, p. 365–372.
- Cloos, M., 1986, Blueschists in the Franciscan Complex of California: Petro-tectonic constraints on uplift mechanisms, *in* Evans, B. W., and Brown, E. H., eds., *Blueschists and eclogites*: Geological Society of America Memoir 164, p. 77–93.
- Dickinson, W. R., and Seely, D. R., 1979, Structure and stratigraphy of forearc regions: *American Association of Petroleum Geologists Bulletin*, v. 63, p. 2–31.
- Dickinson, W. R., and Snyder, W. S., 1978, Plate tectonics of the Laramide orogeny, *in* Matthews, V., III, ed., *Laramide folding associated with basement block faulting in the western United States*: Geological Society of America Memoir 151, p. 355–366.
- Dumitru, T. A., 1988, Subnormal geothermal gradients in the Great Valley forearc basin, California, during Franciscan subduction: A fission track study: *Tectonics*, v. 7, p. 1201–1221.
- Dumitru, T. A., 1989, Constraints on uplift in the Franciscan subduction complex from apatite fission track analysis: *Tectonics*, v. 8, p. 197–220.
- Dumitru, T. A., and Tagami, T., 1991, Fission track thermochronology of the Franciscan accretionary prism, California: *Eos (Transactions, American Geophysical Union)*, v. 72, p. 549.
- Elder, W. P., and Miller, J. W., 1990, Checklists of Jurassic and Cretaceous macrofauna from United States Geological Survey collections within the San Jose 1:100,000 map sheet, California: U.S. Geological Survey Open-File Report OFR 90–534, 27 p.
- Ernst, W. G., 1993, Metamorphism of Franciscan tectonostratigraphic assemblage, Pacheco Pass area, east-central Diablo Range, California Coast Ranges: *Geological Society of America Bulletin*, v. 105, p. 618–636.
- Fuis, G., and Mooney, W. D., 1990, Lithospheric structure and tectonics from seismic-refraction and other data, *in* Wallace, R. E., ed., *The San Andreas fault system, California*, U.S. Geological Survey Professional Paper 1515, p. 207–236.
- Harms, T. A., Jayko, A. S., and Blake, M. C., Jr., 1992, Kinematic evidence for extensional unroofing of the Franciscan Complex along the Coast Range fault, northern Diablo Range, California: *Tectonics*, v. 11, p. 228–241.
- Isozaki, Y., and Blake, M. C., Jr., 1994, Biostratigraphic constraints on formation and timing of accretion in a subduction complex: An example from the Franciscan Complex of northern California: *Journal of Geology*, v. 102, p. 283–296.
- Jayko, A. S., Blake, M. C., Jr., and Harms, T., 1987, Attenuation of the Coast Range ophiolite by extensional faulting and the nature of the Coast Range “thrust,” California: *Tectonics*, v. 6, p. 475–488.
- Maxwell, J. C., 1974, Anatomy of an orogen: *Geological Society of America Bulletin*, v. 85, p. 1195–1204.
- Moxon, I. W., 1988, Sequence stratigraphy of the Great Valley basin in the context of convergent margin tectonics, *in* Graham, S. A., ed., *Studies of the geology of the San Joaquin Basin*: Pacific Section, Society of Economic Paleontologists and Mineralogists, Field Trip Guidebook 60, p. 3–28.
- Murchev, B. L., and Blake, M. C., Jr., 1993, Evidence for subduction of a major ocean plate along the California margin during the Middle to early Late Jurassic, *in* Dunne, G., and McDougall, K., eds., *Mesozoic paleogeography of the western United States, II*: Pacific Section, Society of Economic Paleontologists and Mineralogists, Book 71, p. 1–18.
- Namson, J. S., and Davis, T. L., 1988, Seismically active fold and thrust belt in the San Joaquin valley, California: *Geological Society of America Bulletin*, v. 100, p. 257–273.
- Phipps, S. P., 1984, Mesozoic ophiolitic olistostromes and Cenozoic imbricate thrust faulting in the northern California Coast Ranges: *Geology of the Mysterious Valley area, California* [Ph.D. thesis]. Princeton, New Jersey, Princeton University, 352 p.
- Platt, J. P., 1986, Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks: *Geological Society of America Bulletin*, v. 97, p. 1037–1053.
- Ring, U., and Brandon, M. T., 1994, Kinematic data for the Coast Range fault and implications for exhumation of the Franciscan subduction complex: *Geology*, v. 22, p. 735–738.
- Seiders, V. M., 1988, Origin of conglomerate stratigraphy in the Franciscan assemblage and the Great Valley Sequence, northern California: *Geology*, v. 16, p. 783–787.
- Suppe, J., and Armstrong, R. L., 1972, Potassium-argon dating of Franciscan metamorphic rocks: *American Journal of Science*, v. 272, p. 217–233.
- Unruh, J. R., and Moores, E. M., 1992, Quaternary blind thrusting in the southwestern Sacramento Valley, California: *Tectonics*, v. 11, p. 192–203.
- Unruh, J. R., Ramirez, V. R., Phipps, S. P., and Moores, E. M., 1991, Tectonic wedging beneath fore-arc basins: Ancient and modern examples from California and the Lesser Antilles: *GSA Today*, v. 1, p. 185–190.
- Unruh, J. R., Davis, D. L., and Krueger, V. P., 1993, Early Cretaceous contraction of the northwestern Sacramento Valley forearc basin, California: *Eos (Transactions, American Geophysical Union)*, v. 74, p. 609.
- Unruh, J. R., Loewen, B. A., and Moores, E. M., 1995, Progressive arcward contraction of a Mesozoic-Tertiary fore-arc basin, southwestern Sacramento Valley, California: *Geological Society of America Bulletin*, v. 107, p. 38–53.
- Wakabayashi, J., 1992, Nappes, tectonics of oblique plate convergence, and metamorphic evolution related to 140 million years of continuous subduction, Franciscan Complex, California: *Journal of Geology*, v. 100, p. 19–40.
- Wentworth, C. M., and Zoback, M. D., 1989, The style of later Cenozoic deformation at the eastern front of the California Coast Ranges: *Tectonics*, v. 8, p. 237–246.
- Wentworth, C. M., Blake, M. C., Jr., Jones, D. L., Walter, A. W., and Zoback, M. D., 1984, Tectonic wedging associated with emplacement of the Franciscan assemblage, California Coast Ranges, *in* Blake, M. C., Jr., ed., *Franciscan geology of northern California*: Society of Economic Paleontologists and Mineralogists, v. 43, 163–173.
- Worrall, D. M., 1981, Imbricate low-angle faulting in uppermost Franciscan rocks, south Yolla Bolly area, northern California: *Geological Society of America Bulletin*, v. 92, p. 703–729.

Manuscript received June 27, 1994

Revised manuscript received September 30, 1994

Manuscript accepted October 7, 1994