TECTONICS, VOL. 17, NO. 4, PAGES 558-570, AUGUST 1998

Ophiolitic basement to a forearc basin and implications for continental growth: The Coast Range/Great Valley ophiolite, California

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Abstract. We present a compilation of 18 published models from the length of the Great Valley forearc basin, California, based on seismic reflection, borehole, seismic refraction, gravity, and aeromagnetic data to address long-standing questions about the nature of the basement to the Great Valley, its origin, its tectonic history, and it's mechanism of incorporation into the North American continental margin. The geophysical models permit a 700-km-long, 70-km-wide, complete ophiolite sequence beneath the entire Great Valley. In the northern Great Valley, the ophiolite is overlain by ophiolitic breccia, the ophiolite crust is 7 - 8 km thick, and the mantle section is mostly unserpentinized. Beneath the southern Great Valley, there is no ophiolitic breccia, the crust may be up to 10 - 12 km thick, and the mantle section, if present at all, is serpentinized to such a degree that it cannot be distinguished from Sierran basement or mafic ophiolite members on the basis of velocity or density data. Geochemical, petrological, and paleomagnetic data support suprasubduction zone ophiolite formation at North American paleolatitudes, and geological data and geophysical models are consistent with ophiolite formation by back arc spreading behind an east facing arc. In the north, this was apparently followed by obduction of back arc crust onto older continental basement during the Late Jurassic Nevadan orogeny. In the south, the newly formed intraoceanic arc and back arc apparently collided with the continental margin during the Nevadan orogeny but were not obducted onto it. Instead, the arc and back arc "docked" with the continental margin leaving the arc itself to become the basement to the Great Valley basin. Cretaceous Sierran magmatism then intruded plutons beneath the docked ophiolite and mafic arc. Irrespective of the detailed accretionary history, our cross sections show a rapid pulse of continental growth by ophiolite accretion of more than 500 km^3 km^{-1} in less than 10 Myr.

1. Introduction

Much of western North America, and in particular California, formed as a result of volcanic-arc and subduction-terrane accretion and magmatic addition of batholithic material during the Mesozoic, when the dominant process at the North American margin was subduction [*Ernst*, 1981]. California therefore is an ideal laboratory for investigating continental accretionary growth.

During the Mesozoic, convergence between the Pacific (and earlier) oceanic plates and the North American continental margin resulted in a typical subduction triplet of accretionary prism, forearc basin, and volcanic arc. In the Miocene, the San Andreas fault system formed replacing the subduction margin with a transform margin. This resulted in Mesozoic subduction units becoming trapped east of the San Andreas fault system, where they are preserved today (Figure 1). Subduction continues today north of the Mendocino triple junction along the Cascadia subduction zone which is associated with the Cascades volcanic arc (Figure 1a). The Great Valley forearc basin in California is 700 km long and 100 km wide. This paper focuses on the mode of formation of the forearc basin basement to understand how a 100-km-wide section of oceanic lithosphere became incorporated into the North American continent.

A large magnetic (Plate 1) and gravity anomaly runs along the entire length of the Great Valley forearc basin [*Cady*, 1975]. These anomalies, combined with penetration of mafic lithologies by hydrocarbon exploration wells, were the first evidence presented for mafic and/or partially serpentinized ultramafic material beneath the Great Valley. Since then, many other analyses of geophysical data have concluded that the 700-km-long, 100-km-wide Great Valley basin is directly underlain by mafic and ultramafic material that we refer to as the Great Valley ophiolite [after *Bailey et al.*, 1970] which may be genetically, and in places also physically, related to the Coast Range ophiolite that crops out along the western margin of the Great Valley [*Bailey et al.*, 1970; *Griscom and Jachens*, 1990; *Jachens et al.*, 1995; *Fliedner et al.*, 1996; *Godfrey et al.*, 1997]. In this paper, we use the term, "ophiolite", to mean a complete oceanic crustal sequence that is now part of the continent, rather than its conventional definition [*Penrose Conference Participants*, 1972]. New velocity and density models from both the northern and southern Great Valley require lower density/velocity material beneath the ophiolitic section [*Fliedner et al.*, 1996; *Godfrey et al.*, 1997; H. Benz, personal communication, 1997]. This slower, lower-density material is most likely Sierran basement (Sierra Nevada batholith and/or Foothills Metamorphic Complex) [*Godfrey et al.*, 1997]. Tectonic scenarios which could result in an ophiolite overlying Sierran basement include obduction of allochthonous oceanic crust over older continental basement [*Suppe*, 1979; *Jayko and Blake*, 1986; *Saleeby*, 1986; *Blake et al.*, 1989; *Dickinson et al.*, 1996] or

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Paper number 98TC01536.
0278-7407/98/98TC-01536$12.00

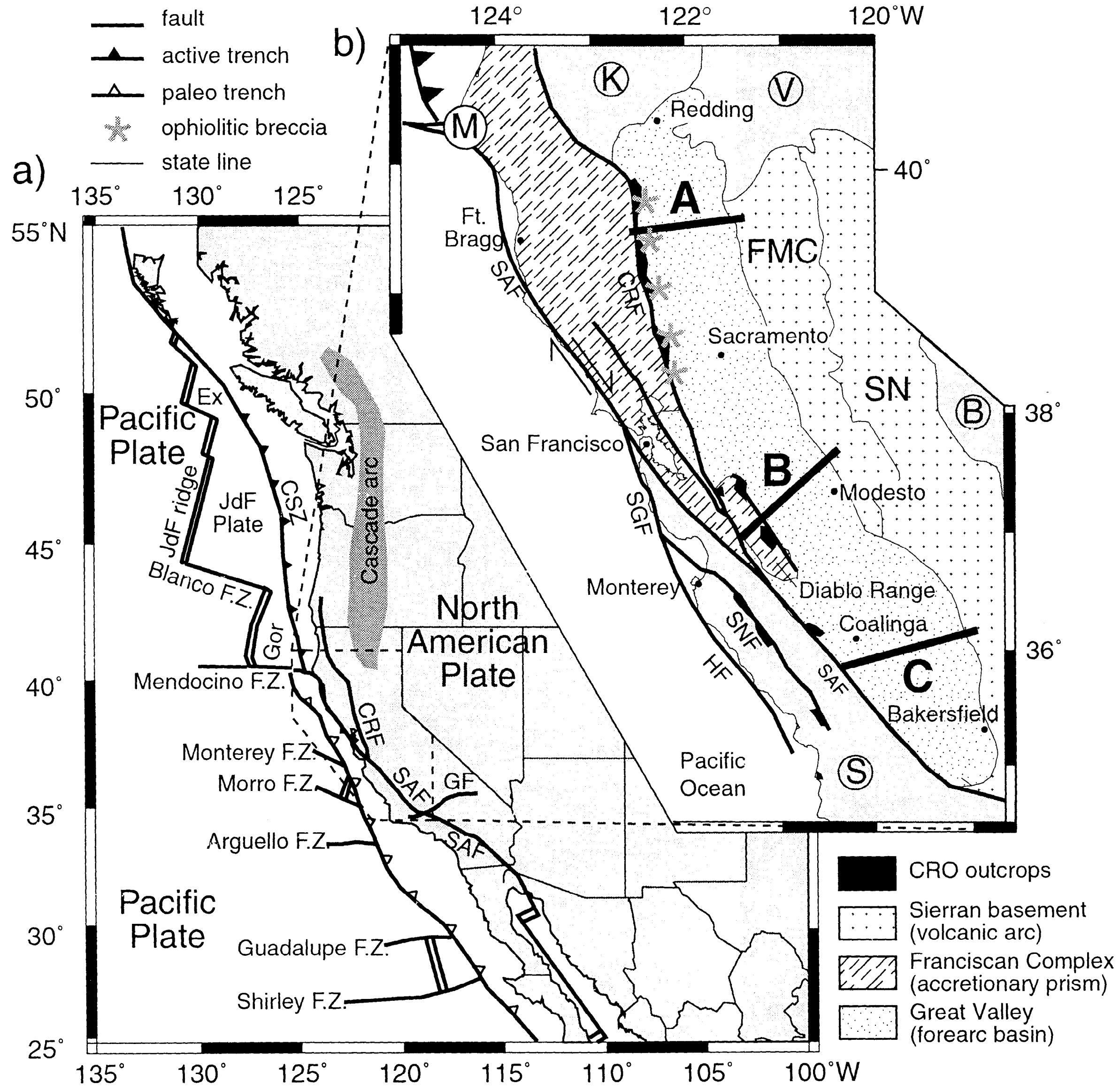


Figure 1. Location maps. (a) Large-scale map of western North America showing present-day plate boundaries. (b) Map of California showing the geological provinces discussed in this paper. Abbreviations are as follows: FZ, fracture zone; Gor, Gorda plate; Ex, Explorer plate; CRF, Coast Range fault; SAF, San Andreas fault; CSZ, Cascadia subduction zone; JdF, Juan de Fuca plate; GF, Garlock fault; SNF, Sur Nacimiento fault; HF, Hosgri fault; SGF, San Gregorio fault; FMC, Foothills Metamorphic Complex; SN, Sierra Nevada batholith; K, Klamath terrane; V, Tertiary and Quaternary volcanics; B, Basin and Range; S, Salinian block; and M, Mendocino triple junction.

younger batholithic intrusions beneath in situ or allochthonous oceanic crust [*Saleeby*, 1986; *Dickinson et al.*, 1996] (Figure 2).

Motivated by the recent publication of the first full-crustal sections across the Great Valley to be constrained by seismic data [*Fliedner et al.*, 1996; *Godfrey et al.*, 1997], we compile all previously published geophysical models from the Great Valley (Plate 1). We conclude that similar ophiolite components are represented along the length of the Great Valley basin, with relatively minor differences between the northern Great Valley (Sacramento basin) and southern Great Valley (San Joaquin basin). We also use our compilation t address long-standing questions about the origin and tectoni evolution of the Great Valley and Coast Range ophiolit [*Dickinson et al.*, 1996]. By understanding the evolution the forearc basement, we learn more about how the forea became part of the North American continent.

2. Tectonic and Geologic Setting

From Mesozoic through Paleogene (about 210 - 29 M time, oceanic crust was being subducted beneath the Nor

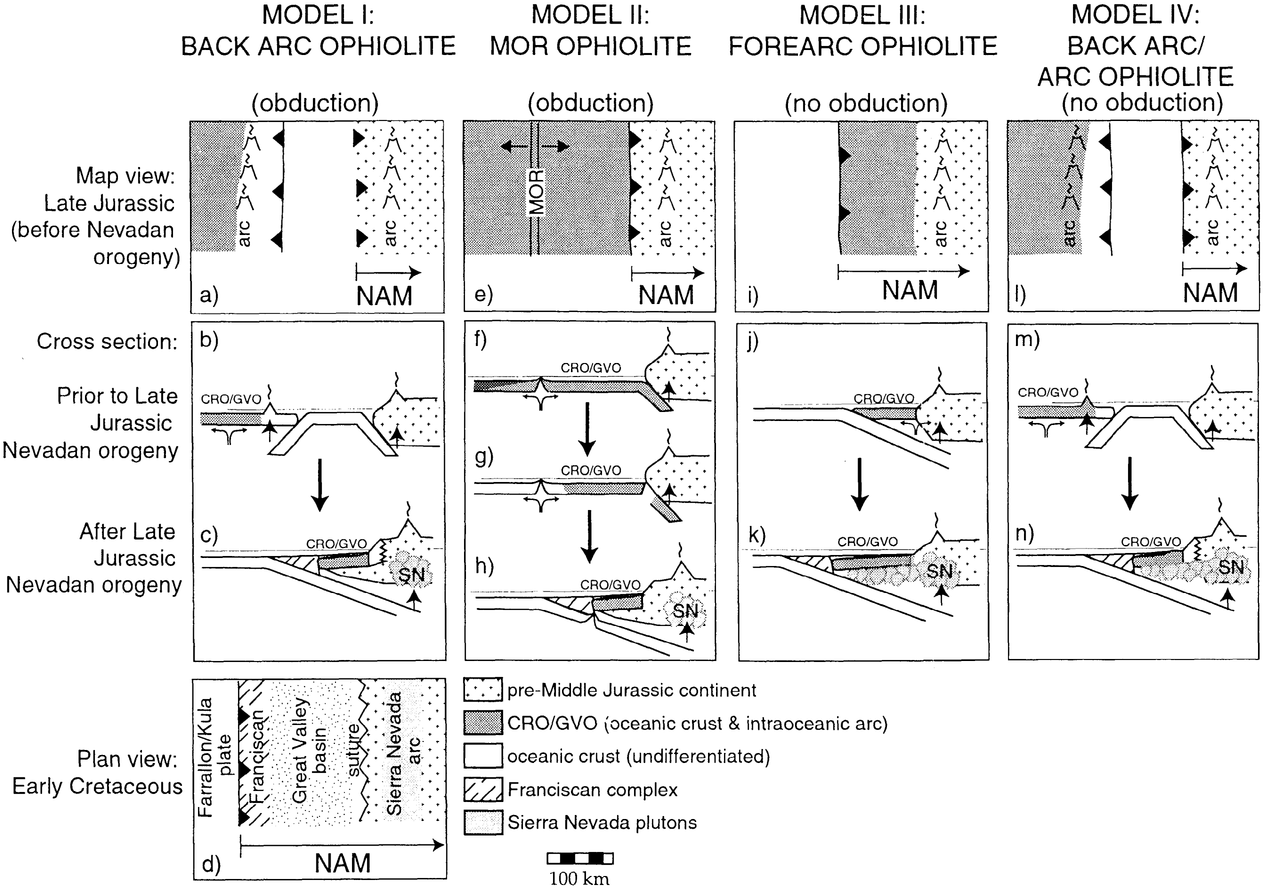


Figure 2. Four tectonic models for the origin of the Coast Range/Great Valley ophiolite (models I - III are based on *Dickinson et al.* [1996] but adjusted for the geometry shown by our geophysical models). (a) - (d) Model I back arc spreading model after W. R. Dickinson [*Dickinson et al.*, 1996] with ophiolite obduction. (e) - (h) (and Figure 2d) Model II mid-ocean ridge model after C. A. Hopson [*Dickinson et al.*, 1996] with ophiolite obduction. (i) - (k) (and Figure 2d) Model III forearc spreading model after J. Saleeby [*Dickinson et al.*, 1996] with no ophiolite obduction. (l) - (n) (and Figure 2d) Model IV back arc spreading, where the ocean arc itself is part of the ophiolite with no ophiolite obduction (based on *Blake et al.*, [1989]). Figures 2b, 2c, 2f - 2h, 2j, 2k, 2m, and 2n are cross-sectional views before and after the Nevadan orogeny. Figures 2a, 2e, 2i, and 2l are map views for each model in the Late Jurassic before the Nevadan orogeny. Figure 2d is a map view for the Late Cretaceous (valid for all models). Abbreviations are as follows: CRO, Coast Range ophiolite; GVO, Great Valley ophiolite; SN, pluton emplacement associated with the Sierra Nevada batholith; MOR, mid-ocean ridge; and NAM, North American plate.

American plate [*Hamilton*, 1969] (Figure 2). At about 29 Ma, the ridge producing the subducting oceanic plate began interacting with the North American margin, creating two triple junctions [*Atwater*, 1970] which migrated away from one another, separated by the lengthening San Andreas transform fault system (Figure 1).

East of the San Andreas fault system, outcrop geology reflects the Mesozoic and Paleogene Andean-type margin; from west to east are exposed the Franciscan Complex (accretionary prism) of the Coast Ranges, Great Valley forearc basin and associated Coast Range ophiolite, and Sierra Nevada magmatic arc, which in the north is associated with the Foothills Metamorphic Complex (Figure 1b) [*Dickinson and Rich*, 1972; *Dickinson*, 1981; *Ernst*, 1981].

The Franciscan Complex represents the Late Jurassic to Miocene accretionary prism of the Franciscan subduction system [*McLaughlin et al.*, 1982; *Blake et al.*, 1988]. It is a mélange of material including graywacke, shale, metasedimentary rocks of varying grade, mafic volcanics, chert, limestone, and ophiolite fragments [*Bailey et al.*, 1964; *Blake and Jones*, 1974]. The Franciscan Complex is subdivided into three belts (Coastal, Central and Eastern) which are further subdivided into terranes and subterranes [*Blake et al.*, 1988; *McLaughlin et al.*, 1993]. The metamorphic grade and age of the Franciscan belts generally increase from west (Coastal belt, prehnite-pumpellyite facies and Late Cretaceous to Miocene) to east (Eastern belt, blueschist facies and Late Jurassic to mid-Cretaceous) [*Blake et* *al.*, 1988; *McLaughlin et al.*, 1993]. East-west shortening across the Coast Ranges caused eastward wedging of Franciscan material beneath the Great Valley forearc basin [*Wentworth et al.*, 1984; *Wentworth and Zoback*, 1990; *Phipps and Unruh*, 1992]. This wedging probably began in the Late Cretaceous related to Franciscan subduction [*Wentworth et al.*, 1984] and is still ongoing today because of compression across the San Andreas fault [*Unruh and Moores*, 1992] as a result of a change in plate motions at about 5 Ma [*Cox and Engebretson*, 1985].

Cenozoic and Mesozoic sedimentary rocks of the Great Valley basin crop out from the latitude of the Mendocino triple junction, the northern termination of the San Andreas fault, to the "Big Bend" in the San Andreas fault close to the Garlock fault [*Jennings*, 1977] (Figure 1). The Great Valley forearc basin is divided into two subbasins: the Sacramento basin (northern Great Valley) and the San Joaquin basin (southern Great Valley). The Great Valley sequence consists of Upper Jurassic (deep ocean and slope environments) to Paleogene (slope, shelf, and nonmarine environments) mudstones, sandstones, and conglomerates [*Bailey et al.*, 1970; *Ingersoll*, 1982]. Cenozoic sedimentary rocks (Oligocene and younger) deposited on the Great Valley sequence include slope, shelf, and nonmarine sediments [*Ingersoll*, 1982].

The Coast Range fault is the present boundary between the Franciscan Complex and the Coast Range ophiolite (CRO) (or Great Valley sequence where there is no CRO) adjacent to the Great Valley north of latitude 36.5°N [*Jayko et al.*, 1987; *Harms et al.*, 1992] (Figure 1b). South of latitude 36.5°N, there are also CRO outcrops west of the San Andreas fault (Figure 1b). CRO is intermittently present along the entire western margin of the Great Valley, north of latitude 36°N. A complete CRO sequence can be reconstructed, but CRO outcrops are generally highly sheared, dismembered, missing sections, and highly serpentinized [*Bailey et al.*, 1970; *Hopson et al.*, 1981]. The missing sections of CRO suggest extension; the most recent motion on the Coast Range fault was normal motion [*Jayko et al.*, 1987; *Harms et al.*, 1992]. Basal Great Valley sequence rocks were deposited directly on rocks of the CRO [*Bailey et al.*, 1970; *Hopson et al.*, 1981]. The CRO formed during the Middle to Late Jurassic (about 173 - 150 Ma) [*Hopson et al.*, 1981; *Saleeby et al.*, 1984; *Mattinson and Hopson*, 1992].

This paper focuses on the Great Valley ophiolite (GVO), the ophiolite sequence postulated to lie buried beneath the Great Valley sequence [*Bailey et al.*, 1964, 1970; *Schweickert and Cowan*, 1975; *Page*, 1981]. The GVO and CRO east of the San Andreas fault may be or may have been physically connected beneath the Great Valley [*Schweickert and Cowan*, 1975; *Godfrey et al., 1997*]. The CRO, however, is significantly thinner in outcrop than either the thickness of the GVO interpreted from geophysical models (this paper) or the thickness of "normal" oceanic crust [*White et al.*, 1992], presumably because of its emplacement and postemplacement history [*Jayko et al.*, 1987; *Harms et al.*, 1992]. The Coast Range fault is believed to have moved as a normal fault 60 - 70 Myr ago, resulting in missing CRO sections and juxtaposing low-grade CRO and GVO directly on high-grade Franciscan Complex [*Jayko et al.*, 1987; *Harms et al.*, 1992]. Because of this structural evidence and because of large thickness variations in both CRO and GVO, we discount an alternative hypothesis that the thin crustal component of the CRO represents slow spreading crust [*Lagabrielle and Cannat*, 1990], whereas the thicker crustal component of the GVO represents "normal" fast spreading crust [*White et al.*, 1992]. The Upper Jurassic to Upper Cretaceous Great Valley sequence was deposited on oceanic crust now represented by the CRO beneath the western Great Valley basin [*Bailey et al.*, 1970; *Evarts*, 1977; *Hopson et al.*, 1981]. Coeval strata are assumed to have been deposited on the GVO in the center of the basin [*Godfrey et al.*, 1997] (the deepest parts of the basin have not been drilled), and uppermost Cretaceous Great Valley sequence was deposited directly on Foothills Metamorphic Complex beneath the eastern part of the basin [*Bailey and Blake*, 1969; *Harwood and Helley*, 1987].

The Sierra Nevada batholith is a continental arc, first formed during the Late Triassic (210 Ma) and continuing into the Late Cretaceous (80 Ma) [*Kistler et al.*, 1971]. It consists of a large number of granitic plutons and in the west tonalitic and gabbroic plutons [*Saleeby*, 1981] that were intruded into Paleozoic and Mesozoic rocks now represented by the Foothills Metamorphic Complex [*Bateman*, 1981] and by diverse roof pendants. The Foothills Metamorphic Complex includes highly deformed Paleozoic active continental margin sequences, early Mesozoic hemipelagic continental clastic and arc-volcanic strata, and ophiolite fragments including the Smartville ophiolite [*Schweickert and Cowan*, 1975; *Saleeby*, 1981]. The Foothills Metamorphic Complex crops out over a wider region (50 - 80 km) in the north than in the south (0 - 40 km) (Figure 1b).

3. Geophysical Models Along and Across the Great Valley Basin

We present models derived from geophysical data (seismic reflection, seismic refraction, gravity, magnetic, and borehole data) collected in or across the Great Valley over the last 14 years, arranged from north to south, and aligned along the magnetic high (Plate 1). All the models discussed have been presented in detail elsewhere. The velocities in the models derived from seismic refraction data are probably accurate to ± 0.1 km s^{-1} in the upper crust and to ± 0.2 km s^{-1} in the lower crust, with 1990s data typically having greatest accuracy, due to reduced station spacing and increased resolution. Density models, in principle, resolve density contrasts but should be good to about ± 0.1 g cm^{-3} in absolute values. Magnetic models provide better constraints on the top surface of a magnetic body than on its base. Absolute magnetization values are far less important than the shape of magnetic boundaries, because measured magnetizations vary by one to two orders of magnitude in otherwise similar rock samples (Table 1). Differences between models derived from different types of data along the same or similar profiles are apparent (compare models 2 and 3 or models 15 and 17, Plate 1). Most models derived from geophysical data are inherently nonunique, so more credence should be given to those models derived from a combination of data types, for example models 3 (derived from seismic, gravity, and magnetic data) and 17 (derived from gravity and magnetic data) (Plate 1).

Table 1. Velocities, Densities, and Magnetizations of Rocks

Lithology	Velocity, km s^{-1}	References	Density, g cm^{-3}	References	Magnetization, A m^{-1}	References
Great Valley rocks	1.6 - 5.3	15	1.7 - 2.7	2, 3, 18	0.1	19
Franciscan Complex	5.5 - 6.2	14	2.21 - 2.99	2, 3, 18	N/A	
Basalt	2.5 - 6.6	10, 12, 16	2.5 - 2.99	2, 3, 12, 16-18	3 - 10	6, 11
Gabbro	6.0 - 7.7	10-12, 16, 17	2.7 - 3.22	3, 11, 12, 16-18	0.03 - 11.8	1, 2, 6-8
Unserpentinized mantle	8.1 - 8.3	12, 16, 19	3.3 - 3.31	16, 19	0 - 4.0	1, 9, 19
10% serpentiized mantle	7.6 - 7.8	13, 19	3.22	19	0.15 - 2.5	19
30% serpentinized mantle	7.0 - 7.4	13, 19	3.06	19	0.15 - 5	19
70% serpentinized mantle	5.9 - 6.3	13, 19	2.78	19	1.0 - 20	19
100% serpentinite	4.9 - 5.3	12, 16, 17, 19	2.21 - 2.57	3, 12, 16-18	0.4 - 60	1-5, 19
Metavolcanics	5.3 - 5.6	16	2.61 - 2.67	2, 16, 18	0 - 35	1, 3
Granite	6.2 - 6.4	16	2.58 - 2.65	3, 16, 18	0.06 - 0.75	1

N/A is data not available. References are as follows: 1, *Cady* [1975]; 2, *Griscom and Jachens* [1990]; 3, *Griscom et al.* [1993]; 4, *Chapman* [1975]; 5, *Blakely and Stanley* [1993]; 6, *Wasilewski and Castro* [1990]; 7, *Kikawa and Pariso* [1991]; 8, *Pariso et al.* [1991]; 9, *Laurent* [1977]; 10, *White et al.* [1992]; 11, *Iturrino et al.* [1991]; 12, *Nichols et al.* [1980]; 13, *Clague and Straley* [1977]; 14, *Stewart and Peselnick* [1977]; 15, *Schock et al.* [1974]; 16, *Christensen and Mooney* [1995]; 17, *Christensen* [1978]; 18, *Thompson and Talwani* [1964]; 19, *Coleman* [1971]; and 20, *Christensen* [1970].

All the geophysical data from the Great Valley permit interpretation of an ophiolite sequence immediately beneath the central part of the Great Valley along the entire length of the basin (models 1 - 18, Plate 1). One or more thrust wedges of Franciscan material [*Wentworth et al.*, 1984; *Godfrey et al.*, 1997] can be interpreted immediately beneath the western margin of the basin along the entire length of the Great Valley (models 2 - 4, 6, 7, 11, 12, and 14 - 18, Plate 1), and lower velocity/density undifferentiated Sierran basement (geophysically represented by the average velocity/density of the diverse Foothills Metamorphic Complex as well as the Sierra Nevada batholith) is apparently present beneath the eastern margin of the basin (models 1 - 3, 5, 7, 11, 12, 13, and 17, Plate 1). Franciscan Complex and Sierran basement extend east and west, respectively, to about the present-day thickest section of Great Valley sediments. Magnetic material is present to some degree beneath the western margin of the basin (models 2, 3, 7, 11, 12, and 17, Plate 1) and may represent a connection between the CRO and GVO (see section 4.2).

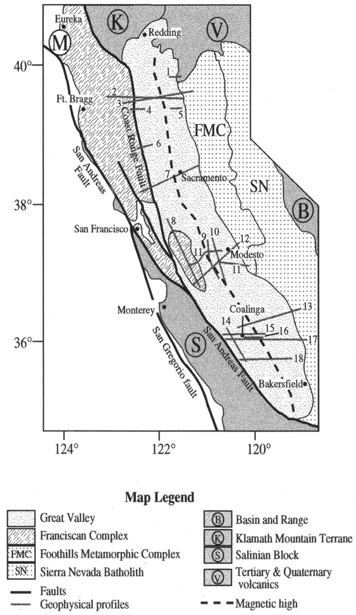
Some of the questions we can address by this compilation of models are as follows: (1) To what depth does ophiolitic material extend? Is the material at the base of the preserved ophiolite section oceanic crust or oceanic mantle? (2) Where is the ophiolite/Sierran basement contact? What orientation does it have? What is the nature of the contact? (3) What happens to the ophiolite beneath the western margin of the Great Valley? (4) How do the answers to these questions vary along the length of the Great Valley? Is there a significant difference between the northern and southern Great Valley?

4. Discussion

We divide the Great Valley into three regions (Sacramento basin, northern San Joaquin basin, and southern San Joaquin basin), and we construct generalized crustal-scale cross sections of the Great Valley (Figure 3), based on all the models available in each region (Plate 1) to address the questions posed above.

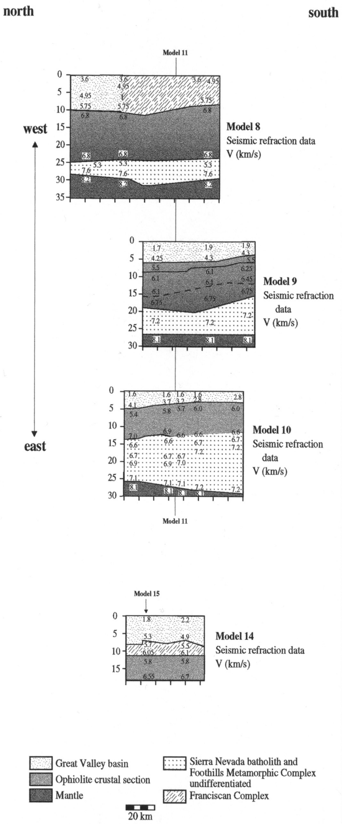
4.1. Thickness of Great Valley Ophiolite and Possible Inclusion of Oceanic Mantle as Well as Oceanic Crust

In the Sacramento basin, the Great Valley ophiolite appears to be a complete ophiolite sequence with about 7 - 8 km-thickness of crust (1, Figure 3a) and about 7 - 8 km of unserpentinized mantle (velocities reaching 8.1 km s^{-1} at about 20 km depth (Table 1)) (2, Figure 3a). A 7- to 8-km-thick crust is reasonable for "normal" oceanic crust [*White et al.*, 1992]. Beneath the ophiolite is 15 km of lower density/velocity material associated with the Sierran basement [*Godfrey et al.*, 1997] which is also seen in the San Joaquin basin (3, Figures 3a - 3c). In contrast, the composite cross sections in the San Joaquin basin show no unserpentinized ophiolite mantle sections (Figures 3b and 3c). Serpentinized mantle has lower velocities/ densities than unserpentinized mantle (Table 1), and we note that bodies interpreted as mafic from velocity/density data could also be interpreted as ultramafic material that has been serpentinized to some degree. The ophiolite section is at least 10 - 12 km thick beneath the San Joaquin basin (Figures 3b and 3c). If this entire section is crust with very little or no mantle component preserved, the San Joaquin basin is underlain by a thickened crustal section compared with normal oceanic crust [*White et al.*, 1992]. Thickened crust might represent intraoceanic island-arc crust or oceanic crust (mid-ocean ridge, forearc, or back arc) that has been thickened either petrologically or structurally (e.g., the Oman ophiolite has been interpreted as overthickened mid-ocean ridge crust [*Nicolas*, 1989]). If, however, some of the 10- to 12-km section is serpentinized mantle, there could be a "normal" thickness of oceanic crust overlying about 5 km of serpentinized mantle.



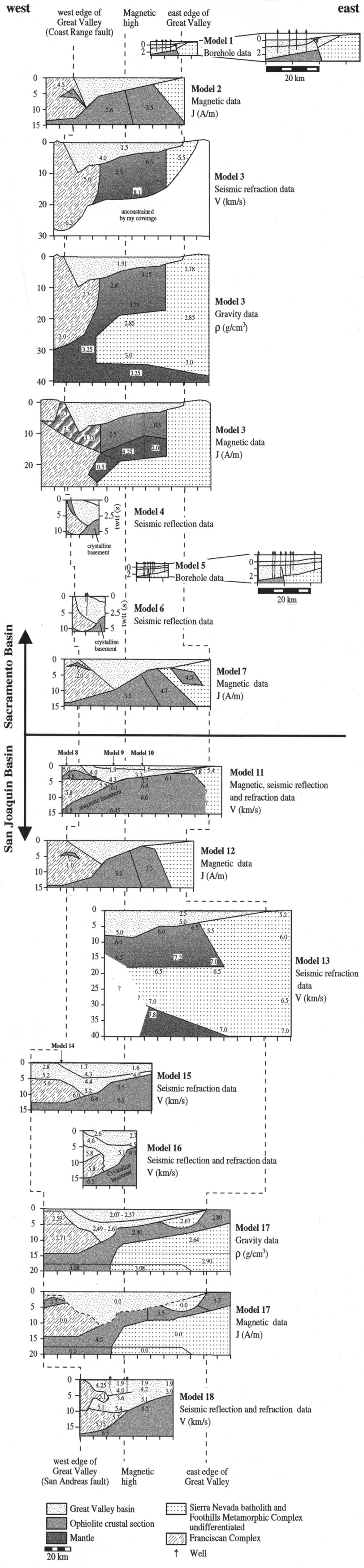
Location map of California showing geophysical profiles across the Great Valley. References are as follows: 1, *Harwood and Helley*, [1987] (well data); 2, *Griscom et al.*, [1993] (gravity and magnetics); 3, *Godfrey et al.*, [1997] (refraction, gravity and magnetics); 4, *Ramirez*, [1992] (reflection); 5, *Harwood and Helley*, [1987] (well data); 6, *Ramirez*, [1992] (reflection); 7, *Jachens et al.*, [1995] (BB' - magnetics); 8, *Blumling and Prodehl*, [1983] (refraction); 9, *Colburn and Mooney*, [1986] (refraction); 10, *Holbrook and Mooney*, [1987] (refraction); 11, *Zoback and Wentworth*, [1986] (CC-1 and CC-2 - reflection and refraction); 12, *Jachens et al.*, [1995] (AA' - magnetics); 13, *Fliedner et al.*, [1996] (refraction); 14, *Walter*, [1990] (refraction); 15, *Walter*, [1990] (refraction); 16, *Wentworth et al.*, [1984] and *Wentworth and Zoback*, [1989, 1990] (SJ-19 - reflection); 17, *Griscom et al.*, [1993] (gravity and magnetics); 18, *Wentworth et al*, [1984] (SJ-6 - reflection and refraction). Basemap after *Fuis and Mooney* [1990].

Longitudinal sections
x2 vertical exaggeration



Patterns in each model represent our interpretation of different geophysical parameters as different tectonic elements. These are not always the same interpretations originally presented by the authors of the models.

Transverse sections, x2 vertical exaggeration



Patterns in each model represent our interpretation of different geophysical parameters as different tectonic elements. These are not always the same interpretations originally presented by the authors of the models.

Models 1 and 5 are shallow sections based entirely on borehole data [*Harwood and Helley*, 1987]. They both show the easternmost Great Valley sediments deposited on top of Sierran granites. They also show a basement fault that juxtaposes Sierran basement to the east against basement of oceanic origin (diorite, gabbro, noritic gabbro, and serpentinite [*Harwood and Helley*, 1987]) to the west. In each case, the basement fault is a projection of a surface fault: the Chico monocline fault in model 1 and a southern extension of the Willows fault in model 5.

Models 2, 7, and 12 are magnetic models, created to fit the large, positive magnetic anomaly present along the length of the Great Valley [*Griscom et al.*, 1993; *Jachens et al.*, 1995]. They show magnetic basement beneath the western 50 - 60 km of the Great Valley and nonmagnetic basement beneath the eastern 25 - 30 km of the basin. We interpret the magnetic basement as ophiolite and the nonmagnetic basement as Sierran basement. Magnetic material (mafic ophiolite or stalled, subducted oceanic plate) extends west at depth beyond the western margin of the Great Valley with a shallow westward dip. There is an "aerofoil" shaped magnetic body within the Franciscan Complex beneath the western margin of the Great Valley that is also interpreted to be ophiolitic material related to the Coast Range ophiolite. The ophiolite/ Sierran basement contact dips east in these models. The depth to the base of the Great Valley basin is constrained by well data and seismic refraction data [*Griscom et al.*, 1993; *Jachens et al.*, 1995]. The models show a horizontal base to the magnetic body, but the data only require that the base is a smooth surface [*Jachens et al.*, 1995]. The base of the magnetic body may correspond to a lithological change which includes a change in magnetic properties or a change in magnetic properties within a single lithological unit or a change in the Curie isotherm [*Jachens et al.*, 1995].

Model 3 is a full crustal model based on seismic refraction, gravity, and magnetic data [*Godfrey et al.*, 1997]. It consists of a velocity model derived from refraction data and a density model obtained by converting the upper crustal velocity model to density and modeling gravity to obtain the deeper part of the density model [*Godfrey et al.*, 1997]. There is high-velocity material beneath the center of the Great Valley, reaching mantle velocities at only 15 km depth. The velocity model is interpreted as showing a 15-km-thick ophiolite sequence (7 - 8 km of ophiolite crust and 7 - 8 km of unserpentinized ophiolite mantle). The density model shows that beneath the ophiolite sequence there is a further 15 km of lower-density material interpreted as Sierran basement, with the present-day Moho at about 34 km depth. The ophiolitic/Sierran basement contact occurs about 15 km from the eastern margin of the Great Valley and appears to be near vertical. The mantle section of the ophiolite dips west and merges with the present-day mantle beneath the western margin of the Great Valley. The high velocities of the crustal ophiolite section do not extend as far as the western margin of the Great Valley. The magnetic model is constrained by the geometry of the density model except that a magnetic body is required beneath the western margin of the Great Valley (striped body on main figure) which we interpret as a mélange of ophiolite and Franciscan rocks.

Models 4 and 6 are based on industry seismic reflection data and borehole data [*Ramirez*, 1992]. The models are based on two parallel seismic lines, T14 (model 4) and T12 (model 6), that cross the western margin of the Great Valley. They both image top of west dipping basement, but there is no control on the lithology of the basement from well data in this region. West dipping reflectors are imaged within the basement on line T14 (model 4), but it is not certain what they represent [*Ramirez*, 1992].

Model 5 is described with model 1.
Model 6 is described with model 4.
Model 7 is described with model 2.

Models 8, 9, and 10 are velocity models from seismic refraction lines recorded parallel to the axis of the Great Valley. Model 8 was mostly recorded in the Diablo Range, part of the Franciscan complex, with the northern end of the line terminating in the Great Valley sequence [*Blumling and Prodehl*, 1983]. Model 8 shows relatively high-velocity rocks beneath the Franciscan section reaching a maximum velocity of 6.8 km s^{-1} at 25 km depth and a velocity inversion to a velocity of 5.3 km s^{-1} which increases to 7.6 km s^{-1} at the 28- to 32-km-deep Moho. There is a first-order velocity discontinuity between the layers interpreted as Franciscan and the higher-velocity rocks. *Blumling and Prodehl* [1983] do not discuss which lithological or tectonic units might be represented in this model. Neither do they discuss the geometry of the Franciscan/Great Valley contact which we show in model 8 as a vertical dotted line for simplicity. We suggest that the relatively thick (15 km), relatively high-velocity (6.8 km s^{-1}) layer represents crustal ophiolite material and that the thin (3 - 7 km) lower-velocity layer beneath the crustal ophiolite represents Sierran basement. Model 9 [*Colburn and Mooney*, 1986] is east of model 8. It shows 21- to 23-km thickness of relatively high-velocity basement from the base of the Great Valley at 4 - 6 km to the Moho at 27 km depth. *Colburn and Mooney* [1986] present two alternative models, but they differ only in the shape of the Moho and the velocity distribution within the basement. They interpreted the 6.1- to 6.25-km s^{-1} layer as Franciscan material, crystalline rocks, or serpentinized ophiolite. They did not interpret the 6.75 km s^{-1} layer but interpreted the 7.2 km s^{-1} layer at the base of the crust as metamorphic and igneous rocks of the Foothills Metamorphic Complex overlying mafic igneous rocks. We interpret the uppermost basement layer (5.5 km s^{-1}) as imbricated ophiolite crust, although this layer could also be interpreted as Franciscan complex. We interpret the 6.1- to 6.25-km s^{-1} layer as the upper part of the ophiolite sequence, the 6.75 km s^{-1} layer as the lower part (crust or serpentinized mantle) of the ophiolite sequence, and the 7.2 km s^{-1} layer as Sierran basement including the Foothills Metamorphic complex. Model 10 [*Holbrook and Mooney*, 1987] changes from north to south. In the north there is about 8 km of relatively high-velocity material (5.4- 7.0 km s^{-1}) overlying lower-velocity material (6.6 km s^{-1}) at about 14 km depth. The velocity of the lower layer increases with depth to 7.1 km s^{-1} at the 26-km-deep Moho. In the south, there is no velocity inversion at 14 km depth, instead, velocity increases gradually from 6.0 km s^{-1} beneath the Great Valley to 6.6 km s^{-1} at 14 km depth to 7.2 km s^{-1} at the 29 km deep Moho. *Holbrook and Mooney* [1987] interpreted this profile as showing ophiolite overlying gabbroic underplate in the north, but they regard the ophiolite as missing in the south since the velocities in the midcrust do not reach 7.0 km s^{-1}. We suggest this profile shows continuous ophiolite along the section, with the base of the ophiolite section more highly serpentinized in the south. We suggest the "gabbroic underplate" is Sierran basement.

Model 11 is derived from a compilation of two seismic reflection lines (CC-1 and CC-2), associated seismic refraction data [*Zoback and Wentworth*, 1986] and magnetic data (R. C. Jachens, unpublished material, 1990). It shows high-velocity, magnetic basement beneath the Great Valley which dips west beyond the western margin of the Great Valley. The eastern extent and maximum depth of the magnetic body are not constrained from the data used in this model.

Model 12 is described with models 2 and 7.

Model 13 is a full-crustal velocity model derived from seismic refraction data [*Fliedner et al.*, 1996]. It shows high velocities beneath the Great Valley basin (6.0 - 7.2 km s^{-1}) with a velocity inversion to 6.5 km s^{-1} at about 18 km depth beneath the central part of the Great Valley. This is interpreted as crustal ophiolite and probably also serpentinized mantle ophiolite, underlain by Sierran basement. The ophiolite/Sierran basement contact appears to dip east and extends from about 60 km west of the eastern Great Valley margin to 40 km west of the margin.

Model 14 is a velocity model along an axial seismic refraction line in the westernmost Great Valley [*Walter*, 1990]. It shows a thin layer of Franciscan material, the toe of a Franciscan wedge beneath the Great Valley, overlying what was interpreted as mafic basement [*Walter*, 1990] with velocities of 5.8 km s^{-1} at the top (12 km depth) down to 6.7 km s^{-1} at the base of the model at 19 km depth. **Model 15** is a profile across the Great Valley that intersects model 14 at its western end. It shows the wedge of Franciscan material beneath the western margin of the Great Valley basin and high-velocity, mafic [*Walter*, 1990] basement beneath the central Great Valley and Franciscan wedge. The basement has velocities of 6.3 - 6.4 km s^{-1} immediately beneath the Great Valley and is only constrained down to about 15 km depth [*Walter*, 1990].

Model 16 is based on seismic reflection data (SJ-3 and SJ-19 [*Wentworth and Zoback*, 1989, 1990]) with supplemental velocities from the seismic refraction model of *Walter* [1990] (model 15). The model shows the top of basement but provides no additional velocity information to that already presented in model 15.

Model 17 is based on both gravity and magnetic data [*Griscom and Jachens*, 1990]. The density model is derived from gravity data, with the base of the Great Valley constrained by seismic data [*Griscom and Jachens*, 1990]. It shows high-density material directly beneath the Great Valley. This high-density material extends beyond the western margin of the Great Valley where it reaches 18 km depth. There are two lower-density regions within the high-density material. One is directly beneath the easternmost part of the basin at a shallow depth, and the other is a large wedge that tapers to the west with a flat base at about 14 km depth. *Griscom and Jachens* [1990] interpret the high-density material as ophiolite and the lower-density material as Sierran basement. The magnetic model is constrained by the density model. It shows that the high-density material immediately beneath the Great Valley is highly magnetic which supports the interpretation of ophiolite. All the material beneath the uppermost basement layer, however, is not magnetic. We interpret all the material beneath 5 - 10 km depth down to the base of the crust as Sierran basement. *Griscom and Jachens* [1990] interpret Moho at 18 km depth and material of density 3.08 g cm^{-3} as continental mantle. Because their result is unconstrained by seismic data and because nearby refraction model 13 suggests Moho at about 30 km depth, we interpret the 3.08 g cm^{-3} material as GVO mantle.

Model 18 is based on seismic reflection data (SJ-6) and coincident seismic refraction data [*Wentworth et al.*, 1984]. The model shows west dipping basement with a velocity of 6.5 km s . The basement was described by *Wentworth et al.* [1984] as "crystalline". We interpret it as mafic, ophiolitic basement. It is not constrained below about 17 km depth.

Plate 1. Geophysical models developed by different authors that are discussed in this paper

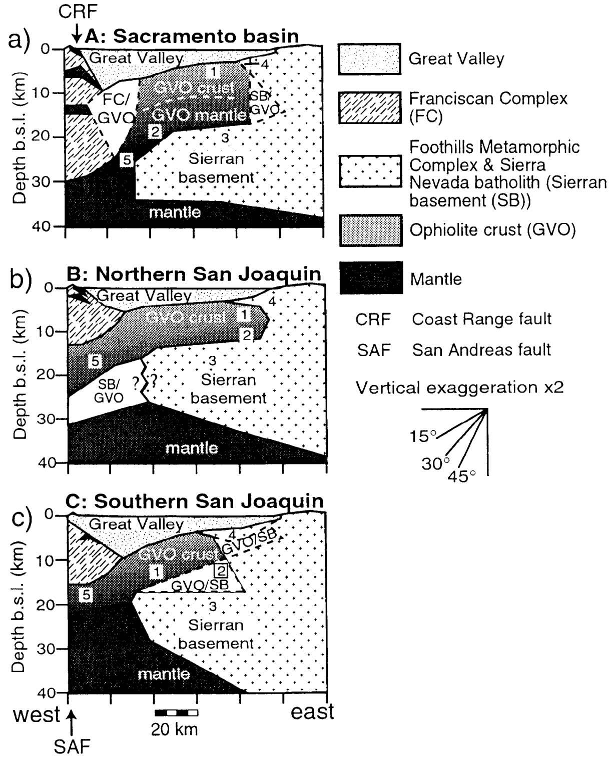


Figure 3. Generalized cross sections across the Great Valley based on all the models in Plate 1. (a) Profile A uses models 1 - 7 (Plate 1), (b) Profile B uses models 8 - 12 (Plate 1), and (c) Profile C uses models 13 - 18 (Plate 1). Numbers in squares are subsurface regions referred to in the text. The profiles along which these models are constructed are shown in Figure 1b.

4.2. Great Valley Ophiolite Beneath Western Margin of the Great Valley Basin

Although geologists have long assumed a connection, there is no velocity/density signature to suggest that the GVO and CRO are connected beneath the western margin of the basin. Magnetic models, however, suggest that highly magnetic mafic and/or serpentinized ultramafic material may connect the two ophiolite segments [*Jachens et al.*, 1995; *Godfrey et al.*, 1997]. Model 3 [*Godfrey et al.*, 1997] (Plate 1) shows a continuous magnetic body beneath the western margin of the Great Valley. *Godfrey et al.* [1997] suggest that tectonic wedging of Franciscan material beneath the Great Valley [*Wentworth et al.*, 1984; *Wakabayashi*, 1992] may have formed a mélange of Franciscan material and GVO/CRO crust and serpentinized mantle that have a velocity/density signature indistinguishable from Franciscan Complex but a strong magnetic signature due to mafic and serpentinized ultramafic components of the mélange. All the magnetic models of *Jachens et al.* [1995] and *Griscom and Jachens* [1990] have an "aerofoil" shaped magnetic body at less than 5 km depth beneath the western margin of the Great Valley (models 2, 7, 11, 12, and 17, Plate 1) rather than a continuous magnetic body. Model 8 [*Blumling and Prodehl*, 1983] (Plate 1), which intersects model 11 in the location of this aerofoil-shaped body, does not show the magnetic body because model 8 is a velocity model based on seismic refraction data, and the aerofoil-shaped body does not have a velocity signature. This is an example of the nonunique nature of magnetic models, for example, magnetic models 2 and 3 both give a good fit to the same data [*Godfrey et al.*, 1997]. Magnetic model 3 [*Godfrey et al.*, 1997] has the advantage that the geometry of the magnetic model is constrained by velocity and density models, while the only part of model 2 [*Jachens et al.*, 1995] that is constrained by seismic data is the base of the Great Valley basin. We therefore suggest that all existing data, however previously interpreted, are consistent with continuity from the GVO to the CRO.

4.3. Location and Orientation of the Ophiolite/Sierran Basement Contact

The ophiolite/Sierran basement (including the Foothills Metamorphic Complex) contact underlies the Great Valley sedimentary section. The lateral position of the contact (4, Figure 3) is about 75 km east of the present western margin of the basin beneath the Sacramento basin and 60 km east of the margin beneath the San Joaquin basin. The geophysical models generally show the contact dipping east (4, Figure 3), although model 3 [*Godfrey et al.*, 1997] suggests it is near vertical down to 18 km depth. The nature of the contact is enigmatic. In the northern Sacramento basin, the shallow expression of the contact is currently associated with east dipping faults (models 1 and 5, Plate 1) that offset the Great Valley sequence and therefore postdate (at least in part) the GVO/Sierran basement contact. All the seismic reflection data presented in this paper are concentrated on the western margin of the basin, and the contact within the basement beneath the eastern margin has not, to our knowledge, been imaged. The subsurface location of the ophiolite/Sierran basement contact is inferred from borehole data and projections of surface fault traces (models 1 and 5, Plate 1).

4.4. Structural Variations Along the Great Valley

The major difference between the northern and southern GVO is that unserpentinized ophiolite mantle extends beneath the whole width of the Sacramento basin (2, Figure 3a). Unserpentinized ophiolite mantle is not present beneath the San Joaquin basin (2, Figures 3b and 3c). Either the San Joaquin section has a thicker crustal section and the mantle section is missing, or the San Joaquin mantle section has been massively serpentinized.

Beneath the Sacramento basin, mafic/ultramafic material west of the present western margin of the basin occurs at deep levels in the crust (20 -30 km depth) (5, Figure 3a), with unserpentinized GVO mantle dipping west to merge with the present-day mantle. In contrast, beneath the San Joaquin basin, mafic material extends beyond the western margin of the basin at midcrustal (about 15 km) depths (5, Figures 3b and 3c). This mafic material could have one of two origins. It may be related to mafic material detected beneath the coast and offshore California and interpreted as stalled subducted slab [*Meltzer and Levander*, 1991; *Tréhu*, 1991] that is now separated from the GVO by the San Andreas fault. Alternatively, the mafic material west of the San Joaquin basin may be a continuation of GVO from the east rather than stalled slab. In this latter case, its continuation farther west and at shallower depths than in the Sacramento basin may be related to a north-south difference in the amount and depth of eastward wedging of Franciscan material. At present, the driving force for ongoing Franciscan wedging is compression across the San Andreas transform [*Wentworth et al.*, 1984; *Wakabayashi*, 1992]. In the north, the San Andreas fault is up to 100 km west of the Sacramento basin, leaving a 100-km-width of Franciscan material available between the San Andreas fault and the Coast Range fault to be involved in eastward thrusting at all levels in the crust (Figure 3a). In the south, the San Andreas fault is the western margin of the San Joaquin basin, leaving only the Franciscan material beneath the western margin of the Great Valley (and the small lateral extent of Franciscan Complex that crops out at the surface in the Diablo Range) to be involved in eastward wedging at relatively high levels in the crust.

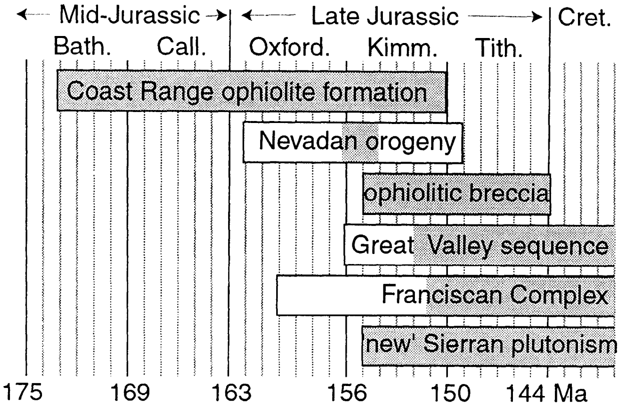


Figure 4. Timeline of major events discussed in the text. Timescale based on *Harland et al.* [1982]. The Sierra Nevada plutons are only those from the Late Jurassic after subduction stepped westward forming the "new" Sierra Nevada [*Schweickert and Cowan*, 1975]. Shading indicates well-constrained ages, and no shading indicates less well-constrained ages. Sources are as follows: Coast Range ophiolite, *Hopson et al.* [1981], *Phipps* [1984], *Ingersoll and Schweickert* [1986], *McLaughlin et al.* [1988], *Robertson* [1989, 1990], and *Mattinson and Hopson* [1992]; Nevadan orogeny, *Schweickert et al.* [1984], *Ingersoll and Schweickert* [1986], *McLaughlin et al.* [1988], *Blake et al.* [1989], and *Robertson* [1989, 1990]; ophiolitic breccias, *Phipps* [1984], *Robertson* [1989, 1990], and *Moxon* [1990]; Great Valley sequence, *Ingersoll and Schweickert* [1986] and *Jayko and Blake* [1986]; Franciscan Complex, *Ingersoll and Schweickert* [1986], *Jayko and Blake* [1986], *Blake et al.* [1988], *McLaughlin et al.* [1988], *Blake et al.* [1989], and *Moxon* [1990], and Sierra Nevada, *Schweickert and Cowan* [1975]. abbreviations are as follows: Bath, Bathonian; Call, Callovian; Oxford, Oxfordian; Kimm, Kimmeridgian; Tith, Tithonian; and Cret, Cretaceous.

5. Origin of the Great Valley Ophiolite

If the Great Valley ophiolite and Coast Range ophiolite are related (physically or genetically) [*Godfrey et al.*, 1997], we can use information about the origin of the Coast Range ophiolite, for which geological, petrological, and geochemical data are available, in conjunction with sparser petrological and lithological information from boreholes within the Great Valley to address the origin of the Great Valley ophiolite. There are three main schools of thought as to the origin of the CRO/GVO which are summarized by *Dickinson et al.* [1996]. A timeline (Figure 4) shows the age information available for the main components involved. Model I (after W. R. Dickinson [*Dickinson et al.*, 1996]) proposes that during the Late Jurassic, the CRO formed by seafloor spreading in a back arc setting behind an east facing intraoceanic island arc (Figures 2a and 2b). This island arc collided with the west facing Sierran continental arc after the intervening oceanic lithosphere was consumed during a Late Jurassic collisional event (the Nevadan orogeny). The geophysical models (Figure 3) all suggest GVO overlies Sierran basement. We can modify model I by requiring that the Nevadan orogeny not only dock the ophiolite against the older continental margin but also obduct the ophiolite onto the Sierran basement (Figure 2c). A new subduction zone (Franciscan subduction) initiated to the west leaving the CRO/GVO in a forearc setting (Figures 2c and 2d). Subduction continued at the new trench, forming the Franciscan Complex, with the subducting slab dipping beneath the continental margin and obducted ophiolite. Model II (after C. A. Hopson [*Dickinson et al.*, 1996]) proposes that the CRO formed at a paleoequatorial mid-ocean ridge (Figures 2e and 2f). It was then transported north to the latitude of the North American continental margin along strike-slip faults, where it docked with the continent during the Nevadan orogeny. Again, in order to obtain the geometry seen in the geophysical models, we need to modify this model by obducting the CRO/GVO onto the older continent during the Nevadan orogeny (Figure 2h). Franciscan subduction initiated as the subduction zone jumped west leaving the CRO/GVO in a forearc setting (Figure 2h). Model III (after J. Saleeby [*Dickinson et al.*, 1996]) proposes that the ophiolite formed in situ by seafloor spreading in a forearc setting in response to transtension due to slab rollback (Figures 2i and 2j), and was therefore not accreted to the continent during a collision (Figure 2j). In this case, the Nevadan orogeny, which resulted in significant crustal shortening in the Sierra Nevada [*Schweickert et al.*, 1984], must be viewed as a highly compressive event, rather than a collisional event. To fit regional geological data, the extension that allowed the ophiolite to form by seafloor spreading must have been relatively local and related to slab rollback, whereas compression associated with the Nevadan orogeny was regional and occurred after ophiolite formation (Figure 4). To get Sierran basement beneath the GVO in this model requires that plutons associated with Sierran magmatism are emplaced not only beneath the axis of the Sierra Nevada arc but also westward beneath the newly formed ophiolite (J. Saleeby, personal communication, 1996) (Figure 2k).

Hagstrum and Murchey [1996] revisited the paleomagnetic data from the Coast Range ophiolite and concluded that previous paleolatitude determinations were based on a remagnetized component. Analysis of the primary magnetization, which had previously been overlooked, suggests that the CRO formed at North American paleolatitudes (about 35°N) rather than at paleoequatorial latitudes. A revision to model II therefore no longer requires a large northward translation component. Geochemical analyses of CRO samples suggest that the southern CRO (Diablo Range and farther south, Figure 1b) and parts of the northern CRO are calc-alkaline rocks comparable with island-arc rocks, while samples from the remainder of the northern CRO sites are comparable with enriched mid-ocean ridge basalts or ocean-island tholeiites [*Shervais and Kimbrough*, 1985]. Petrological analyses also suggest a suprasubduction zone setting rather than a mid-ocean ridge setting [*Evarts*, 1977; *Saleeby*, 1986; *Blake et al.*, 1989; *Wentworth et al.*, 1995]. Geochemical and petrological data therefore appear to support a suprasubduction zone setting rather than an open-ocean mid-ocean ridge. In the light of these data, we omit further discussion of model II as a possible origin for the CRO/GVO. *Blake et al.* [1989] suggested that the southern CRO (Diablo Range and south, Figure 1b) represents an island arc that formed above oceanic basement, consistent with the thicker mafic sections shown in our San Joaquin models (Figures 3b and 3c), while the northern CRO has a more oceanic character (forearc, back arc, or mid-ocean ridge), consistent with the 7- to 8-km mafic section above unserpentinized mantle shown in our model (Figure 3a). We next attempt to use our geophysical models to distinguish between CRO/GVO formation in a back arc (model I), forearc (model III), or as part of an island arc [*Blake et al.*, 1989].

5.1. Geophysical Models With Additional Geological Information: Distinguishing Which Model(s) Best Describes the Origin of the GVO/CRO and Its Incorporation Into the North American Continent

Model 1 which requires collision and obduction of the ophiolite onto the continent (Figure 2) can explain the ophiolite overlying Sierran basement by thrusting the entire ophiolite section onto the older continental margin. In this case, the velocity/density inversion (at about 20 km depth) in our geophysical models (models 3, 8, 10, 13, 14, and 17, Plate 1) represents a major thrust surface, similar to the shear zones interpreted as a detachment in the ultramafic sections of the exposed 400-km-long, 50- to 100-km-wide Oman ophiolite [*Nicolas*, 1989]. In this model, the eastern east dipping ophiolite/Sierran contact would be a major collisional suture zone. Model III (Figure 2) requires Cretaceous Sierran magmatism to have been responsible for intruding the lower-velocity/density material not only beneath the axis of the magmatic arc but also west of the main magmatic arc beneath the ophiolite that formed in a forearc setting (J. Saleeby, personal communication, 1996). This may be plausible beneath the San Joaquin basin, which formed adjacent to granitic and tonalitic intrusive bodies, but is scarcely so for the Sacramento basin, which formed adjacent to the Foothills Metamorphic Complex which represents the basement into which the Sierran magmas intruded, with the intrusives for the most part cropping out farther east. In the case of model III, the eastern east dipping ophiolite/Sierran basement contact may be an extensional feature related to forearc spreading. The east dipping contact shown in our three profiles (Figure 3) possibly resembles the thrust wedging now well documented [*Fuis*, 1998] in the Franciscan on the west side of the Great Valley (Figure 3) and so may be indicative of a collisional or at least accretional setting, rather than an extensional setting, suggesting support for model I rather than model III.

Model I requires major uplift of the ophiolite onto the continent during obduction. This would cause erosion of the uplifted oceanic crust, the debris from which might be expected to accumulate in the newly forming forearc basin. An ophiolitic breccia zone up to 100 m thick is documented between the uppermost Coast Range ophiolite members and the lowermost Great Valley sequence rocks at the western margin of the Sacramento basin. *Phipps* [1984] reports olistostromes (including the Pope Creek breccia of *Wagner* [1975]) that consist of ophiolitic debris mixed with Great Valley sequence mudstones. These olistostromes are believed to have been deposited on the serpentinites representing the Coast Range ophiolite in this area and grade upward into well-bedded Great Valley sequence rocks. Stratigraphic relationships demonstrate that the chaotic olistostrome unit formed within 20 Myr of the formation of the ophiolite itself [*Phipps*, 1984] (Figure 4), implying that the obducted lithosphere was young, presumably hot and buoyant and resistant to subduction, facilitating obduction. A similar age relationship is seen in the Oman ophiolite, where ophiolitic conglomerates derived from erosion of the obducted ophiolite were deposited within 10 Ma of the formation of the oceanic crust [*Nicolas*, 1989]. *Hopson et al.* [1981], *Robertson* [1989], and *Moxon* [1990] also report an ophiolitic breccia zone that was deposited on the uppermost members of the Coast Range ophiolite at Paskenta, Thomes Camp, South Fork or Elder Creek, Elk Creek, and Wilbur Springs. This breccia zone also has lowermost (Upper Kimmeridgian - Lower Tithonian) Great Valley sequence rocks deposited directly on top of it at the western margin of the Sacramento basin. In contrast, neither the breccia zone nor the ophiolitic olistostromes are seen in the San Joaquin basin, where well-bedded Great Valley sequence mudstones directly overlie Coast Range ophiolite [*Hopson et al.*, 1981].

This indirect evidence for greater ophiolite uplift in the north than in the south is consistent with much geological evidence that the Nevadan orogeny, widely interpreted as a collisional event [*Schweickert et al.*, 1984], resulted in more intense deformation in the northern Sierra Nevada than in the southern Sierra Nevada [*Schweickert et al.*, 1984].

5.2. Summary and Model

We here summarize all the key data we wish to explain.

In the northern Great Valley we contend the following: (1) The Nevadan orogeny was an intense compressional, probably collisional event, (2) plutons of the main Sierra Nevada batholith occur only east of the eastern margin of the Great Valley, (3) ophiolitic breccia overlies the Coast range ophiolite, (4) the Great Valley ophiolite crust is interpreted from geophysical models to be about 7- to 8-km thick, and (5) petrology and geochemistry suggest a suprasubduction affinity for the CRO/GVO, and the ophiolite could be back arc, arc, or forearc crust.

In the southern Great Valley we contend the following: (1) The Nevadan orogeny was a less intense compressive event, (2) Sierra Nevada plutons are found adjacent to and beneath the eastern margin of the Great Valley, (3) there is no ophiolitic breccia overlying the Coast range ophiolite, (4) geophysical models suggest the Great Valley ophiolite crust may be up to 10- to 12-km thick, and (5) petrology and geochemistry suggest suprasubduction formation of the GVO/CRO and may be indicative of arc material rather than forearc or back arc crust.

We now present a model for the formation and emplacement of the Great Valley ophiolite. We favor seafloor spreading in a back arc environment associated with an east facing arc for ophiolite formation, similar to that shown by model I (Figures 2a and 2b). We envisage different modes of emplacement for the ophiolite, however, from north to south. In the north, we suggest that the east facing arc and back arc crust collided with and were obducted onto the older continental arc (Figure 2c). Erosion of the ophiolite during obduction caused ophiolitic breccias to be deposited on top of the ophiolite as the earliest deposits of the Great Valley basin. In the south, where the Nevadan orogeny was less intense, the east facing arc and back arc crust (Figures 2l and 2m) collided with the older continental margin but were not obducted onto it (Figure 2n), explaining the lack of ophiolitic breccias in the southern Great Valley. The arc became the basement to the newly forming Great Valley basin. After the Nevadan orogeny, Franciscan subduction initiated west of the Coast Range/Great Valley ophiolite, and the associated Sierra Nevada magmatism was responsible for intruding plutons beneath the newly formed ophiolite in the southern Great Valley (Figures 2n and 2d). By the Early Cretaceous, the entire Coast Range/Great Valley ophiolite had been assimilated into the North American continent (Figure 2d), representing a very rapid (< 10 Myr) pulse of mafic/ultramafic accretionary growth. North America continued to grow by the accretion of Franciscan terranes until at 29 Ma the San Andreas fault system initiated.

6. Conclusions

Geophysical data from the entire Great Valley permit a 700-km-long and 70-km-wide complete ophiolite section as basement to the Great Valley forearc basin. In the northern Great Valley, the GVO includes an unserpentinized mantle section, whereas in the southern Great Valley the mantle section, if present, is serpentinized to such a degree that it cannot be distinguished from Sierran basement or ophiolite crust on the basis of velocity and density. Wedging of Franciscan material has truncated the western margin of the ophiolite at middle- to lower-crustal depths in the north, but wedging was confined to upper crustal depths in the south, allowing the ophiolite to extend west beyond the western margin of the Great Valley at midcrustal depths in the San Joaquin basin.

We favor the formation of oceanic crust in a back arc basin (model I of *Dickinson et al.* [1996]) for the origin of the Great Valley/Coast Range ophiolite. We propose a new hybrid model for Nevadan ophiolite incorporation into the North American continent, with obduction of a back arc ophiolite in the north and collision but not obduction of oceanic arc and back arc ophiolite in the south. After the Nevadan orogeny, the Franciscan subduction zone initiated west of the Coast Range/Great Valley ophiolite, and Sierra Nevada magmatism emplaced plutons beneath the ophiolite in the south but only east of the ophiolite in the north. In a short period of the Late Jurassic, the entire Coast Range/Great Valley ophiolite was incorporated into the North American continent to serve as basement to the nascent Great Valley basin.

Acknowledgments. We thank R. Coleman and S. Graham for discussion and H. Benz for his seismic-tomography results ahead of publication. Thorough reviews by M. C. Clark, R. J. McLaughlin, and D. W. Scholl made this a better manuscript. Research was funded by NSF grant EAR-9218209 (Continental Dynamics).

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(Received August 5, 1997;
revised April 24, 1998;
accepted May 7, 1998.)