SEDIMENTOLOGY AND TECTONIC IMPLICATIONS OF OPHIOLITE-DERIVED CLASTICS OVERLYING THE JURASSIC COAST RANGE OPHIOLITE, NORTHERN CALIFORNIA

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ABSTRACT. Strongly dismembered remnants of the Middle-Upper Jurassic (169-161 Ma) Callovian-Oxfordian Coast Range Ophiolite are sandwiched between the younger Franciscan metamorphic subduction-accretion complex below and the depositionally overlying Great Valley forearc sequence. Five to 10 Ma after crustal genesis, crustal tension and inferred detachment faulting exposed all levels of the ophiolite, including ultramafics, to erosion on the seafloor (Kimmeridgian-early Tithonian; about 155 Ma). Mass-wasting of submarine ophiolite fault scarps generated 0 to 500 m thick talus wedges (breccia unit) composed of detached blocks, megabrecia, clast-supported breccia, conglomerate, minor matrix-supported rudite, and small volumes of sand and mud. Clasts locally include exotic calc-alkaline extrusive and intrusive rocks, derived from an unexposed volcanic arc. Deposition resulted from a combination of slumping and sliding, rock fall, debris flow, turbidity, and traction currents. A 0 to 10 m thick conformably overlying, early Tithonian, transitional unit contains ophiolite-derived and subordinate silicic volcanic and tuffaceous sediment which was probably arc-derived. Local well rounded clasts in both units suggest localized uplift above wave base. Basal terrigenous hemipelagic and turbiditic sands and minor tuffs, derived from the North Sierra and Klamath areas, progressively sealed the faulted seafloor during late Tithonian to Early Cretaceous time when the ophiolite was in a forearc setting above a continentward-dipping subduction zone. Erosion of ophiolite basement highs, tensional growth-faulting, serpentinite diapirism, and serpentinite debris flow deposition all took place during this time. In the light of possible modern oceanic and ancient ophiolitic examples, it is concluded that the Coast Range Ophiolite breccia unit was created above a subduction zone in an oceanic setting (166-161 Ma), associated with arc volcanism (about 160-155 Ma). The "arc-ophiolite" then drifted continentward and docked with the Pacific continental margin during the Nevadan orogeny (about 155 Ma). During the initiation of continentward (eastward) (Franciscan?) subduction, the newly assembled ophiolitic forearc underwent crustal tension, associated with the breccia accumulation. This was apparently followed by short-lived uplift, giving rise to a texturally more mature overlying transitional unit (lower Tithonian). Great Valley
Group deep-water terrigenous sediments then accumulated in a forearc setting during a phase of eastward subduction and accretion of the Franciscan Complex (middle Tithonian-Early Cretaceous).

INTRODUCTION

This paper describes and interprets the sedimentology and tectonic setting of coarse grained sedimentary rocks, including breccia and conglomerate, that unconformably overlie deeply eroded remnants of a Jurassic ophiolite complex in the Coast Ranges of northern California (north of San Francisco). The Coast Range Ophiolite (Bailey, Blake, and Jones, 1970; Hopson, Mattinson, and Pessagno, 1981) underlies the upper Mesozoic Great Valley Group, a classic deep-water forearc succession (Dickinson and Seely, 1979; Ingersoll, 1982). Studies of oceanic crust (Arcyana, 1975; Cyagor 11 Group, 1984; Ballard and Moore, 1977) and ophiolite complexes (Barrett and Spooner, 1977; Simonian and Gass, 1978) reveal similar ophiolite-derived clastics in a number of modern and ancient tectonial settings including spreading ridges and transform faults. The North California ophiolite-derived sediments were attributed previously to disruption of oceanic crust (Hopson, Mattinson, and Pessagno, 1981), faulting, uplift, and deep erosion (Phipps, 1984: Blake and others, 1987), genesis along an oceanic fracture zone (Harper, Saleeby, and Norman, 1985), erosion of an arc (Lagabrielle and others, 1986), or to formation in a strike-slip controlled pull-apart basin located along the Pacific continental margin (McLaughlin and Ohlin, 1984).

To set the scene for a discussion of the ophiolite-derived breccias, I will first summarize alternate views on the structural and tectonic setting of the Coast Range Ophiolite in relation to the Franciscan Complex and the Great Valley Group. The stratigraphy and age relations of the ophiolite remnants will then be reviewed. Following this, the lithostratigraphy and facies of the ophiolite-derived rudaceous sediments and the basal facies of the Great Valley Group will be described and interpreted. Modern and ancient comparative settings will be discussed. Finally, a model is presented in which the northern California ophiolite-derived sediments accumulated by mass-wasting of seafloor fault scarps related to a phase of pervasive crustal tension of the ophiolitic basement. In the light of modern and ancient comparisons, it is hypothesized that crustal tension and rupture of ophiolitic basement took place in a newly created forearc above a continentward-dipping subduction zone, synchronous with initial Franciscan subduction-accretion.

REGIONAL SETTING

Ophiolite-derived clastic sediments constituting a 0 to 500 m thick breccia unit and a 0 to 10 m thick overlying transitional unit, unconformably overlie the Coast Range Ophiolite in northern California (Bezore, 1969; Bailey, Blake, and Jones, 1970; Bailey and Blake, 1974; Evarts, 1977; Hopson, Mattinson, and Pessagno, 1981; fig. 1). Successions at individual localities are summarized in figure 2.
Fig. 1. Outline tectonic map of California showing the locations of the Coast Range Ophiolite remnants, specifically those studied in the Northern Coast Ranges.
Fig. 2. Summary logs of the Coast Range Ophiolite remnants exposed in Northern California; lithologic data modified from Hopson, Mattinson, and Pessagno (1981); radiometric ages are also summarized.
The Coast Range Ophiolite is tectonically underlain by, or in high-angle fault contact with, mainly high-pressure metamorphic assemblages of the Franciscan Complex (Blake and others, 1987a). The Franciscan Complex is generally interpreted as a subduction-accretion complex (Hamilton, 1969; Ernst, 1970), influenced by thrusting and strike-slip (McLaughlin and Ohlin, 1984) along the Pacific continental margin (Blake and Jones, 1974, 1981; McDowell and others, 1984) during late Mesozoic to Recent time. The boundary between the low metamorphic grade Coast Range Ophiolite and the blueschist metamorphic Franciscan Complex varies from a single high-to-low-angle fault (for example, Paskenta area) to a complex variably oriented zone of disruption and melange formation (Wilbur Springs area, fig. 1). Traditionally, this contact is known as the Coast Range thrust (Bailey, Blake, and Jones, 1970), more aptly termed the Coast Range fault (Jayko, Blake, and Harms, 1987), and is variously interpreted as the sole thrust of an ophiolite nappe, with up to 100 km of westward displacement; an imbricate thrust zone (Korsch, 1983), which was the slip plane of a late Mesozoic subduction zone during initial eastward Franciscan subduction (Hamilton, 1969; Dickinson, 1970; Ernst, 1970); as the roof thrust of a Franciscan imbricate thrust wedge (Wentworth and others, 1984); as a high-angle reverse fault entraining upward slivers of basement (similar to the Jurassic Galice Formation, Southern Oregon) (Jayko and Blake, 1986); as a late-Mesozoic-Tertiary normal fault related to detachment and extensional unroofing of the Franciscan Complex (Platt, 1986; Jayko, Blake, and Harms, 1987); as a Late Cretaceous-early Tertiary pre-San Andreas strike-slip fault; and/or, as a Quaternary-Recent fault (Earth Science Associates, 1980), possibly related to San Andreas tectonics and uplift of the Franciscan Complex following passage of the Menocino triple junction.

The ophiolite and its overlying clastic sediment cover pass upward disconformably, without any regionally discernable structural or metamorphic break, into Late Jurassic and younger, mainly deep-water terrigenous turbiditic successions of the Great Valley Group (Ingersoll, 1982). The Great Valley Group developed above an eastward-dipping subduction zone between the Franciscan trench to the west and the Sierra Nevada continental margin arc to the east.

Utilizing the terrane concept, Howell, Jones, and Schermer (1985) viewed the Franciscan Complex, the Coast Range Ophiolite, and the traditional Great Valley sequence as part of a collage of crustal units assembled by mainly strike-slip along the Pacific borderland (Blake, Howell, and Jones, 1982; Blake, Jayko, and McLaughlin, 1985). The Coast Range Ophiolite, the underlying serpentinite melange, and the overlying Great Valley sediments in the northern Californian (in the Paskenta area) were assigned to the Elder Creek Terrane (Blake, Jayko, and McLaughlin, 1985). In this scenario, the lower Great Valley sequence along the western margin of the Sacramento Valley could be grossly allochthonous (despite the apparent absence of major regional
stratal discontinuities). Unfortunately, paleomagnetic studies have proved of little value since the rocks are remagnetized (Frei and Blake, 1987). However, the close similarities between the compositions of conglomerates in the Franciscan Complex and the adjacent Great Valley Group appear to oppose strike-slip faulting between these two units (Seiders and Blome, 1988). The writer's working assumption is that the Franciscan Complex and the Great Valley Group were essentially coupled in Late Mesozoic time, as in classic plate tectonic models (Hamilton, 1969; Ernst, 1970; Dickinson, 1970), but that variable degrees of strike-slip disruption parallel to the active continental margin have taken place (Ernst, 1984).

**STRUCTURAL SETTING**

The studied outcrops occur along the western edge of the Sacramento Valley and as fault-bounded units within the Franciscan Complex to the southwest. Magnetic and gravity modelling of the contact between the Great Valley Group and the Franciscan Complex in the south of the area (that is east of Clear Lake) (fig. 1; Ruppel, 1971; Griscom, 1983) indicate that relatively flat-lying basement extends about 50 km westward below the eastern edge of the Franciscan outcrop (fig. 3). This basement is interpreted as Coast Range Ophiolite exposed to the surface only locally (Wilbur Springs antiform, fig. 3; Griscom, 1983; Wentworth and others, 1984; Jayko and Blake, 1986; McLaughlin and Ohlin, 1984; McLaughlin and others, 1985).

Augite and quartz-hornblende diorite, of probable ophiolitic affinity, were recovered from deep wells along the crest of a magnetic anomaly 55 km east of Wilbur Springs (fig. 1; McLaughlin and others,

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**Fig. 3.** Simplified cross section from the western edge of the Sacramento Valley across Clear Lake to the Geyser Peak area; for location see figures 4 and 5. Modified from McLaughlin and Ohlin (1984).
1985), supporting the idea that ophiolitic, or "arc-ophiolitic," crust underlies the Sacramento Valley.

Farther north, along the western edge of the Sacramento Valley near Paskenta (fig. 1), the Coast Range Ophiolite and associated sediments crop out in the upturned edge of a major steeply-dipping homocline (Brown, 1964; Bailey, Blake, and Jones, 1970; Fritz, 1975; Maxwell, 1974; Suppe, 1978, 1979; Blake and others, 1984). This homocline is cut by the Paskenta Fault Zone, a major northwest-southeast trending shear zone of apparent left-lateral offset. Depending on the orientation of bedding at the time of deformation, the fault zone can be attributed to either original Late Cretaceous left-lateral strike-slip faulting (Jones and Irwin, 1971; Wentworth and others, 1984) or to northwest-southeast directed tensional (growth) faulting during Late Jurassic-Early Cretaceous (Suchecki, 1984; Vogel, 1985). In the Paskenta area, the contact between the Coast Range Ophiolite and the Franciscan Complex to the west is a high-angle fault (Hopson, Mattinson, and Pessagno, 1981; Jayko, Blake, and Harms, 1987), still seismically active (Earth Science Associates, 1980). Seismic reflection data are interpreted to indicate the existence of several imbricate wedges of Franciscan rocks between the underlying crustal basement and the originally depositionally overlying Great Valley Group (Wentworth and others, 1984).

Farther south (fig. 1), the Coast Range Ophiolite and its sediment cover occur as narrow elongate, mainly north-south trending, fault-bounded slivers within the Franciscan Complex (fig. 3). The Coast Range ophiolite remnants can be interpreted simply as down-faulted klippen from an originally laterally extensive ophiolite nappe (Bailey, Blake, and Jones, 1970; Platt, 1986), as having been thrust eastward onto the western margin of the Sierra Nevada basement (Suppe, 1979), or, alternatively, as slivers of ophiolitic basement beneath the Sacramento Valley entrained northward within the Franciscan Complex mainly by strike-slip prior to 50 Ma (Blake, Jayko, and McLaughlin, 1985; McLaughlin, 1978; McLaughlin and Ohlin, 1984). More regionally, the basement of the Great Valley under the Sacramento Valley has been interpreted, based on seismic, gravity, and magnetic data (Cady, 1975), as mafic, possibly ophiolitic crust in the west, but as Sierran-Klamath continental crust in the east. Large aeromagnetic and gravity anomalies extending for about 600 km along the center of the Sacramento Valley apparently mark the suture between these crustal units (Blake, Zietz, and Daniels, 1977).

Interpretation of the Coast Range Ophiolite and its sediment cover in northern California must, therefore, be consistent with the following major post-depositional structural events: (1) genesis and metamorphism of the Franciscan Complex inboard of a trench (Hamilton, 1969; Ernst, 1970; Dickinson, 1970); (2) deposition of the Late Jurassic-Early Cretaceous base of the Great Valley Group mainly in a forearc area, locally affected by extension, growth faulting, subsidence (Suchecki,
and serpentine diapirism (Carlson, 1984a, b, c); (3) Mid Cretaceous-early Tertiary compressional deformation of the Great Valley Group near the edge of the Sacramento Valley (Suppe, 1978, 1979); (4) fault disruption and melange formation, partly related to inferred northward strike-slip, prior to 50 Ma (McLaughlin and Ohlin, 1984; Blake, Jayko, and McLaughlin, 1985); (5) Neogene-Quaternary (post 3 Ma) reactivation and uplift, possibly related to onset of San Andreas-style tectonics following northward passage of the Mendocino triple junction (McLaughlin and Ohlin, 1984; McLaughlin and others, 1986).

THE COAST RANGE OPHIOLITE IN NORTHERN CALIFORNIA

The Coast Range Ophiolite in northern California is restricted to remnants exposed along the western margin of the Sacramento Valley, mainly in the Paskenta area, and as fault-bounded slivers, composed of serpentinized harzburgite tectonite farther west within the Franciscan Complex (fig. 1). The ophiolite, overlying breccia, and the base of the Great Valley Group exhibit zeolite and phrenite-pumpellyte facies metamorphism in contrast to the structurally underlying high-pressure metamorphism of the Franciscan Complex (Bailey and Jones, 1973). Lower stratigraphical levels of the ophiolite are commonly cut out by the Coast Range fault, whereas higher levels are eroded. At one extreme, the ophiolite is reduced to several tens of meters of sheeted dikes, for example at Pope Creek and Fir Creek (fig. 1), while elsewhere almost a complete, but thin, ophiolite succession can be pieced together in fault-bounded blocks, for example near the South Fork of Elder Creek in the Paskenta area (Blake and others, 1987a, b) and in the Geyers area (McLaughlin and Pessagno, 1978; McLaughlin and Ohlin, 1984). Locally, the plutonic complex is cut by dioritic and rare quartz diorite dikes, possibly reflecting off-axis, or arc-type, magmatic activity (South Fork of Elder Creek; Blake and others, 1987a, b).

The orientation of the sheeted complex can be compared with the (near) paleohorizontal recorded in fine-grained overlying sediments. On this basis, the sheeted complex varied from sub-vertical, for example, at Pope Creek, to sub-horizontal, at Fir Creek and Geyser Peak when overlying sedimentation began (fig. 1). Assuming the dikes were originally sub-vertical when intruded, they have been variably rotated, either at the spreading center, as proposed in the Troodos ophiolite, Cyprus (Verosub and Moores, 1981; Varga and Moores, 1985), and/or later during crustal rupture and overlying breccia formation (see below). Alternatively, Hopson, Mattinson, and Pessagno (1981) believe the Sheeted Complex is a primary sill complex in many areas. Minor preserved extrusive successions, for example, at Black Mountain (Geyers area, fig. 1) are sub-alkaline tholeiites (Lagabrielle and others, 1986). Major and trace element geochemical studies of the coeval central California Coast Range Ophiolite remnants are compatible with an above subduction zone genesis in a marginal basin (Blake and Jones,
implications of ophiolite-derived clastics

1974), arc-related (Evants, 1977), or intra-arc setting (Shervais and Kimbrough, 1985): occurrences of high-magnesian (boninitic) lavas arguably favor a forearc position (Shervais, 1987; Robertson, 1989). Proximity of a volcanic arc at Paskenta is strongly suggested by clasts in the breccia composed of calc-alkaline diorite, quartz diorite, granodiorite, andesite, and dacite, in addition to typical Coast Range Ophiolite rocks (Lagabrielle and others, 1986).

Pb/U zircon ages are reported from the Harbin Springs ophiolite remnant in northern California (fig. 1). Hornblende plagiogranite pegmatites that intrude the upper part of the gabbro succession yield a concordant U/Pb zircon age of 169 Ma and a concordant U/Pb sphene age of 164 Ma (J.M. Mattinson, in McLaughlin and Ohlin, 1984). Similar U/Pb ages were obtained from the central California Coast Range Ophiolite remnants (Mattinson, 1980; Hopson, Mattinson, and Pessagno, 1981). By contrast, most K/Ar ages from the northern California ophiolite remnants are younger (161-141 Ma). In the South Fork of Elder Creek (fig. 1) hornblende from a gabbro dike cutting clinopyroxene cumulate, but not the overlying breccia unit, gave a K-Ar hornblende age of 151 ± 5 Ma (Lanphere, 1971) (155 Ma using new time constants). Hornblende gabbro K-Ar hornblende ages are 163 ± 5 Ma and 141 Ma (fig. 2). Elsewhere in the Paskenta area, McDowell and others (1984) obtained an age of 166 ± 3 Ma on ophiolitic gabbro and 162 ± 3 Ma on a gabbro block in ophiolitic melange farther north. Two other gabbro samples yielded ages of 143 ± 3 Ma and 144 ± 3 Ma (McDowell and others, 1984, see also Fritz, 1974). Elsewhere, at Wilbur Springs (McLaughlin and others, 1985) hornblende gabbro in serpentinite near the base of the ophiolite remnant (figs. 1, 5B) gave K-Ar amphibole ages of 140 Ma and 143 ± 7 Ma (Rich, 1971; McDowell and others, 1984). Thrusting, folding, and mobilization of serpentinite took place after basal Great Valley Group deposition (Suppe, 1979; Carlson, 1984a, b, c), apparently resulting in uralitization of mafic intrusive rocks and consequent loss of Ar (Hopson, Mattinson, and Pessagno, 1981); K-Ar ages <155 Ma appear to be anomalous and should probably be reassessed.

Oxfordian-Kimmeridgian and Tithonian ages for interlava radiolarian cherts were reported from Black Mountain (Geyers area, fig. 1), although it is doubtful if these cherts are truly interlava sediments (see below). An apparently anomalous lower Tithonian radiolarian age (zone 2, subzone 2b) was assigned to red, non-tuffaceous, cherts interbedded with basaltic pillow lavas at Wilbur Springs (near Eagle Rock, fig. 1; Pessagno, 1977). More geochemical work is needed to determine if these lavas are typical Coast Range Ophiolite extrusives, or if they show more affinities with coeval, lower Tithonian, high-Ti basalts farther north at Stonyford. These rocks are interpreted as a collapsed seamount, sandwiched between the Great Valley Group and the Franciscan Complex (Hopson, Mattinson, and Pessagno, 1981: MacPherson and Phipps, 1988). In summary, the northern California Coast Range
Ophiolite is interpreted to have formed at a spreading center above a subduction zone, from 169 to 161 Ma, in a setting associated with arc-type magmatism.

SEDIMENTARY COVER OF THE OPHIOLITE

In Northern California the Coast Range ophiolite is conformably overlain, first, by the breccia unit, 0 to 500 m of mainly coarse-grained, texturally immature, sediments of almost entirely ophiolitic provenance; then, by the transitional unit, 0 to 10 m of more texturally mature mainly ophiolite-derived clastics, including some sediment exotic to the local ophiolitic basement (figs. 4, 5, 6). Above this, the "Knoxville Formation" at the base of the Great Valley Group comprises terrigenous mudstone, sandstone, volumetrically subordinate rudite and tuffaceous sediments (Ingersoll, 1982, 1983). The widely spaced nature of the ophiolite-derived clastic sediment outcrops suggests that a formalized stratigraphy is not appropriate.

The breccia unit is dated locally. In the Paskenta area, at Crowfoot Point (figs. 1, 6), *Buchia rugosa* in the mudstone indicates an upper Kimmeridgian age (Jones, 1975; Pessagno, 1977), while lower Tithonian radiolarians (zone 2, subzone 2A) were obtained from this horizon (Pessagno, 1977; Hopson, Mattinson, and Pessagno, 1981). It should be noted that in the European radiolarian scheme (Baumgartner, De Wever, and Kocher, 1980; Baumgartner, De Wever, and Murchey, 1987) Pessagno's zones 1 and 2 (Pessagno, 1976, 1977; Pessagno, Blome, and Longorio, 1984) are dated as somewhat older, with zone 1 extending to Callovian. In the South Fork of Elder Creek a 155 ± 5 Ma aged dike is truncated at the unconformity above, establishing a maximum age for the breccia unit (Blake and others, 1987), equivalent to Kimmeridgian on the Harland and others (1982) time scale.

Nature of Basal Contact with the Ophiolite

At a classic locality, the South Fork of Elder Creek in the Paskenta area (figs. 6, 7, log 15; 8, vi; Blake and others, 1987a) a 40 to 100 m thick breccia unit succession unconformably overlies layered wehlite and clinopyroxenite. Mapping by Jayko and Blake (1987; fig. 6, inset) has, however, established that in this area the breccia unit is underlain by basic lava, sheeted dikes, and plutonic rocks in adjacent fault-bounded blocks. The ophiolite, breccia unit, and the base of the Great Valley Group (but apparently not the structurally underlying Franciscan Complex) are cut by faults of apparent left-lateral offset (for example in Digger Creek, fig. 6). These faults are related to the Paskenta Fault Zone, interpreted either as Late Cretaceous strike-slip faults (Jones and Irwin, 1971) or as tensional dip faults (Vogel, 1985).

Farther south, in the Harbin Springs ophiolite remnant (figs. 4C, 7, log 2; 8, v) an intact breccia unit overlies highly sheared plutonic ophiolitic rocks including pegmatitic gabbro. At Mt. St. Helena (figs. 4B, 7, log 3; 8, iv) the breccia unit, again little underformed, is underlain by gabbro and sheeted dikes (Hopson, Mattinson, and Pessagno, 1981). At
Fig. 4. Geological sketch maps of ophiolite remnants and associated sediments: (A) Geyser area, (B) Mt. St. Helena area, (C) Anderson Springs and Harbin Springs area; inset: outline tectonic map of the area as a whole; map data modified from McLaughlin (1978).

this locality the breccia is cut by isolated (undated) sub-vertical diabase dikes with well developed chilled margins. Petrographic study shows the dikes are less altered than the adjacent highly weathered rudites of the breccia unit. By contrast, along the road to the Geyser (figs. 4A, 7, log 5: 8, iii), the breccia unit unconformably overlies a small fault-bounded
Fig. 5. Geological sketch maps of ophiolite remnants and associated sediments: (A) outline tectonic map of area bordering the Sacramento Valley between Lake Berryessa and Clear Lake (based on Geological Map of California, 1977); (B) Wilbur Springs area (based on McLaughlin and others, 1985); (C) Pope Creek area (based on Wagner, 1975); (D) Fir Creek area (based on Moiseyev, 1970).

body of sheeted dikes or sills which crop out much more extensively on Geyser Peak across a ravine to the west (fig. 4A). In other areas, the breccia unit overlies sheeted complex, as at Pope Creek (figs. 5C, 7, log 8; 8, i) and Fir Creek (figs. 5D, 7, log 7). At Wilbur Springs, the breccia unit overlies basaltic pillow lava and hyaloclastite, with a low-angle unconformity (figs. 5B, 7, log 9; 8, ii). Along the north side of Pope
Fig. 6. Geological sketch maps of the Paskenta area bordering the Sacramento Valley; inset: large-scale map of the South Fork of Elder Creek area, based on Jayko and Blake (1988), Blake and others (1987).

Creek (figs. 7, log 8; 8, i) a transition is well exposed from sheared and tectonically disrupted sheeted complex rocks to the breccia unit above. The underlying sheeted complex comprises numerous steeply-dipping microgabbro and diabase dikes, with thick glassy chilled margins and screens of olivine gabbro, norite, and diorite (Wagner, 1975). Stratigraphically, within 8 m of the contact the sheeted complex is tectonically brecciated, cracks being infilled with hard white pectolite and albite. Individual brecciated chilled dike margins can be traced through the breccia. However, several meters up-section the sheeted complex is increasingly brecciated. The more finely crystalline diabase dikes with thick chilled margins typically remain intact, while more coarsely crystalline diabase and gabbro host rocks are more brecciated. Over several tens of centimeters upsection, the clasts become more sub-angular to sub-rounded, with a matrix of small angular rock fragments and albite. Several meters higher a sharp depositional contact is exposed with well stratified breccia, which dominates the overlying breccia unit.
Elsewhere, the basal relations are still controversial. Near the summit ridge of Black Mountain, within the Geyser Peak ophiolite remnant (fig. 4A) volcaniclastic, "tuffaceous" cherts are reported to contain radiolarians dated ?Oxfordian-Kimmeridgian (upper part of zone 1) to lower Tithonian (zone 2, subzone 2A; Pessagno, 1976: Pessagno, Blome, and Longorio, 1984). These cherts were originally mapped by McLaughlin (1978: see also McLaughlin and Pessagno, 1978) as being within the lower part of the ophiolitic extrusive succession, implying an Oxfordian or younger age for at least part of the extrusive succession. By contrast, noting that in the central Coast Ranges cherts of similar lithology and inferred age range are only known depositionally overlying the ophiolite, Hopson, Mattinson, and Pessagno (1981) suggested that these sediments represent an original sedimentary cover to the ophiolite that was later downfaulted into the extrusives. In an attempt to shed light on this controversy, a new succession was measured along the higher, eastern slopes of Black Mountain (fig. 4A). Tens of meter-thick successions of bedded ophiolite-clastic rudite and sandstone are overlain there by about 25 m of irregularly weathering tuffaceous volcaniclastic sediments. Further detailed mapping is needed to establish the relation of this succession with the tuffs mapped within basalt by McLaughlin (1978). It should be noted, however, that indurated nearly monomict ophiolite-derived sediments are commonly difficult to distinguish from magmatic ophiolitic rock in the field, particularly when weathered and poorly exposed. Some outcrops, previously mapped as ophiolite, have turned out to be of clastic origin when studied by optical microscopy. Examples include outcrops of the eastern slopes of Black Mountain mapped as basaltic extrusives (fig. 4A), the base of the breccia unit on the Geyers road (fig. 4A), and parts of the outcrop mapped before as gabbro in the Harbin Springs remnant (fig. 4C).

Lithostratigraphy

The breccia unit ranges from 0 to 500 m, with a typical thickness of 100 to 250 m. In general there is no overall change in clast- and/or grain-size from the base to the top of the succession. Massive to poorly stratified breccia dominate the successions at Pope Creek and Fir Creek (figs. 7, logs 7, 8; 8, i). Poorly sorted conglomerate and breccia with outsized blocks characterize relatively thin (about 40 m) successions in the South Fork of Elder Creek (fig. 7, log 15). By contrast, several kilometers southward, the breccia unit reaches its maximum known thickness, about 500 m in Digger Creek (figs. 7, log 14; 8, vi). There, the base of the succession comprises about 200 m of mega-breccias, with huge, up to 10 m sized, detached blocks, overlain first by about 200 m of crudely stratified clast-supported breccia, then by generally upward-fining successions of clast- and matrix-supported breccia, sandstone, and mudstone, which extend southward to Crowfoot Point (fig. 7, log 13).

Elsewhere, the breccia unit is typically finer-grained. At Mt. St. Helena (fig. 7, log 3; 8, iv) the basal about 45 m of the succession
comprise ophiolite-derived sandstone and mudstone that coarsen upward, passing into nearly massive conglomerate and coarse-grained sandstone. Along the road to the Geysers (fig. 7, log 6: 8, iii), the succession is dominated by tightly cemented, massive, coarse-grained sandstone and fine-grained rudite.

At one locality, in the core of the Wilbur Springs anticline (fig. 3: 7, log 9: 8, ii), up to several hundred meters of basaltic pillow lava, lava breccia, and hyaloclastite are unconformably overlain by 0 to 80 m of laterally variable conglomerate with scattered, well rounded clasts. The succession passes upward into 80 m of volcaniclastic sandstone, mudstone, basalt lava blocks, redbedded pillow lava, and both lava- and diabase-derived breccia. These heterogeneous basalt-derived sediments are then conformably overlain by mudstone and sandstone of the Tithonian aged base of the Great Valley Group.

**Lithofacies**

*Mega-brecia.*—Mega-brecia is defined as extremely coarse breccia, with angular clasts in excess of 1 m in size. Mega-brecia is extensively developed on vegetated hillslopes between Digger Creek and Crowfoot Point in the Paskenta area (figs. 6, 7, log 14: 8, vi), where it is seen to overlie depositionally sheared plutonic ophiolitic rocks, where local unfauluted contacts are preserved. Lagabrielle and others (1986) mapped the mega-brecia as coherent mafic lava flows and lava-brecia unconformably overlying plutonic ophiolite rocks in the area extending from near the South Fork of Elder Creek to Crowfoot Point (fig. 6). By contrast, the writer observed that the lower 200 m of the succession comprise up to tens of meter-sized detached blocks, mainly composed of vesicular flow-banded basic, intermediate, and silicic lava and silicic tuff breccia. Individual lava blocks are tabular, often aligned parallel to gross bedding. Poor exposure conceals relationships between the largest blocks. However, smaller, meter-sized, blocks are definitely epiclastic sedimentary breccia, composed of nearly monomict angular lava clasts. Overlying this mega-brecia is an about 150 m thick interval containing numerous large blocks of unsheared gabbro and diabase, lava and tuff-brecia, in turn overlain by clast-supported polymict breccia.

*Isolated detached blocks.*—Detached blocks up to 10 m in size locally occur within rudite. In the South Fork of Elder Creek (figs. 6, 7, log 15), disorganized conglomerate contains several meter-long irregular blocks of mafic lava breccia and spalled pillow basalt with a glassy hyaloclastite matrix. On the north bank of the stream the breccia is cut by several small basaltic dikes with locally intact chilled margins (fig. 7, log 15). However, these dikes are restricted to within the lava block and do not extend into the adjacent breccia. Elsewhere in the Paskenta area at Digger Creek (fig. 7, log 14; 8, vi), thick breccia and conglomerate include up to 4.5 m-sized angular detached blocks of brecciated diabase, containing an intact thin basaltic dike, and up to 5 m-sized detached blocks of pillow lava. Farther south, at Crowfoot Point (fig. 7, log 12),
**Figure 7**

### Side Key

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane lamination</td>
<td></td>
</tr>
<tr>
<td>Micro-Cross-lamination</td>
<td></td>
</tr>
<tr>
<td>Graded bedding</td>
<td></td>
</tr>
<tr>
<td>Burrowing</td>
<td></td>
</tr>
<tr>
<td>Intraclasts</td>
<td></td>
</tr>
<tr>
<td>Plant detritus</td>
<td></td>
</tr>
<tr>
<td>Bed thickness in meters ($&gt;10$ cm)</td>
<td></td>
</tr>
<tr>
<td>Bed thickness in cm ($&lt;10$ cm)</td>
<td></td>
</tr>
<tr>
<td>Bed thickness range up to 0.15 m ($&gt;10$ cm)</td>
<td></td>
</tr>
<tr>
<td>Average clast size ($&gt;10$ cm)</td>
<td></td>
</tr>
<tr>
<td>Clasts range in size up to 0.15 cm ($&gt;10$ cm)</td>
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### Main Key

<table>
<thead>
<tr>
<th>Grain-size</th>
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<tbody>
<tr>
<td>Fine</td>
<td>Mudstone</td>
</tr>
<tr>
<td>Medium</td>
<td>Siltstone/Sandstone</td>
</tr>
<tr>
<td>Coarse</td>
<td>Conglomerate</td>
</tr>
<tr>
<td></td>
<td>Breccia</td>
</tr>
<tr>
<td></td>
<td>Reworked pillow lava</td>
</tr>
<tr>
<td></td>
<td>Lava breccia</td>
</tr>
<tr>
<td></td>
<td>Radiolarian chert</td>
</tr>
<tr>
<td></td>
<td>Siliceous sediment</td>
</tr>
<tr>
<td></td>
<td>Limestone concretions</td>
</tr>
<tr>
<td></td>
<td>Siliceous tuff</td>
</tr>
<tr>
<td></td>
<td>Basalt/Diabase</td>
</tr>
<tr>
<td></td>
<td>Gabbro/Peridotite/Serpentinite</td>
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</tbody>
</table>

### Colors

<table>
<thead>
<tr>
<th>Color</th>
<th>Description</th>
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<tr>
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<td>Gy</td>
<td>Gray</td>
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<td>Pu</td>
<td>Purple</td>
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<tr>
<td>R</td>
<td>Red</td>
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<tr>
<td>W</td>
<td>White</td>
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### Bed Measured

<table>
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<tr>
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<tbody>
<tr>
<td>Bed measured</td>
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<tr>
<td>Bed interpolated</td>
</tr>
<tr>
<td>Well exposed</td>
</tr>
<tr>
<td>Poorly exposed</td>
</tr>
<tr>
<td>Section continues (not measured)</td>
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</table>

### Faults

<table>
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</thead>
<tbody>
<tr>
<td>Fault</td>
</tr>
<tr>
<td>No exposure</td>
</tr>
<tr>
<td>Meters of additional exposure</td>
</tr>
</tbody>
</table>

### Ophiolitic basement

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheeted dikes/sills</td>
</tr>
<tr>
<td>Gabbric rocks</td>
</tr>
<tr>
<td>Ultramafic rocks</td>
</tr>
<tr>
<td>Serpentinite</td>
</tr>
<tr>
<td>Shearing</td>
</tr>
<tr>
<td>Fault</td>
</tr>
<tr>
<td>No exposure</td>
</tr>
<tr>
<td>Meters of additional exposure</td>
</tr>
</tbody>
</table>
Fig. 8. Composite logs of the main sedimentary successions overlying ophiolite remnants in northern California. Based on the detailed logs given in Figure 7.
clast- and matrix-supported breccia interbedded with mudstone include up to 4.5 m thick elongate units of disrupted mafic pillow lava and up to 7 m long by 0.6 m thick tabular lenses of internally disrupted red recrystallized radiolarian chert. Three, en echelon, lenticular chert bodies are locally present within very disrupted pillow lava and monomict (sedimentary) lava breccia. These cherts are detached blocks and not true pelagic interbeds within the breccia. Elsewhere, at Pope Creek (figs. 5C, 7, log 8), tabular blocks of diabase and microgabbro, up to several meters-long by up to 1.3 m wide, occur within clast-supported breccia. These blocks are detached fragments of dikes that still exhibit well developed chilled margins and contain numerous xenoliths. At Wilbur Springs (fig. 5B, 8, ii), up to several-meter-long, angular blocks of radiolarian chert and metalliferous pelagic limestone also occur in basal rudaceous facies.

Angular clast-supported breccia.—Angular clast-supported breccia commonly forms the base of the breccia unit but also comprises the entire succession locally (fig. 7). At Pope Creek (figs. 5C, 7, log 8) all the breccia unit comprises repeated meter-scale breccia lenses. Crude stratification is defined by preferential long-axis clast orientation and trains of elongate blocks of basic, intermediate, and acid composition extrusives (fig. 7, log 8). No systematic variation in clast-size is observed, clasts being typically 0.1 to 0.3 m to locally 0.9 m in size, with isolated meter-sized detached blocks (see above). Larger clasts tend to be sub-angular to sub-rounded, while smaller ones are more angular. The matrix comprises angular centimeter- to millimeter-sized rock chips with a local albite cement. Many clasts are tightly interlocking and show evidence of intense compaction and pressure solution (Wagner, 1975), as shown in figure 9. Similar, but thinner, less well exposed, clast-supported breccia overlies ophiolitic sheeted diabase at Fir Creek (figs.

![Fig. 9. Tracing of a photograph of a polished slab. White, clasts; black, matrix (modified after Wagner, 1975). Note the complex interlocking clast fabric. At Pope Creek angular clasts, mainly composed of glassy tholeiitic basalt, were pressed into one another as shown. Wagner (1975) attributed this to pressure solution beneath the Great Valley sequence overburden. Similar fabrics have not been noted elsewhere. The writer agrees with a pressure solution origin and tentatively suggests that extreme overpressuring may have taken place along faults that juxtaposed the Coast Range Ophiolite with the Franciscan Complex.](image-url)
5D, 7, log 7). By contrast, in the Harbin Springs ophiolite remnant (figs. 4C, 7, log 1), clast-supported breccia is restricted to near the base of the breccia unit. Monomict gabbro-derived breccia predominates, with angular clasts up to 0.7 m in size, with little or no matrix. Elsewhere, on the road to the Geysers (figs. 4A, 7, log 5) ophiolitic sheeted complex rocks are overlain by meter-sized angular diabase blocks in a coarse sandstone matrix at the base of the breccia unit. Similar clast-supported breccias are also common in the Paskenta area (figs. 7, log 14: 10A, B).

Clast-supported conglomerate and breccia.—This is the most volumetrically abundant lithofacies consisting of crudely stratified, to massive, immature poorly sorted, breccia and conglomerate, differing from the breccia described above mainly by being more heterogeneous, with sub-rounded and locally well rounded clasts.

In the South Fork of Elder Creek, a 40 to 100 m of succession of this lithofacies is composed of angular to sub-rounded clasts, mostly 0.6 m in diameter, and rare outside blocks, up to several meters in size. The clasts are ophiolite-derived and are composed of vesicular basic, intermediate, and silicic extrusives and plutonic rocks (see above). A crude stratification, defined by clast alignment, is visible only in the topmost several meters of the succession, where clasts are more rounded (fig. 11B). Thicker successions of this lithofacies (about 100 m) are exposed several kilometers to the south in Digger Creek (figs. 6, 7, log 14). The following units are observed there in ascending stratigraphic order: unsorted basalt-derived breccia with a volcanioclastic matrix; nearly monomict gabbro-derived breccia, with clasts up to 4.5 m in size; diabase- and basalt-derived breccia with a red siliceous mudstone matrix; matrix-supported breccia with interstitial volcanioclastic sandstone and lastly, oligomict breccia, with clasts of most, if not all, the ophiolitic lithologies. Above the Harbin Springs ophiolite remnant (figs. 4C, 7, log 1), breccia at the base of the succession is overlain by more texturally-mature clast-supported breccia and conglomerate, ranging from crudely stratified (calcite-cemented) mainly gabbro- and diabase-derived breccias to softer-weathering more basalt-derived conglomerate. Clasts are typically sub-angular to sub-rounded; typical clast-size ranges from 0.2 to 0.4 m. Some beds show distinct size-sorting and include common unusually well rounded clasts. At Mt. St. Helena (figs. 4B, 7, log 3) abundant poorly stratified clast-supported breccia, about 100 m thick, is present only in the upper levels of the breccia unit. There, up to 10 m thick, repeated intervals are interbedded with pebbly mudstone and volcanioclastic sandstone, containing angular to sub-angular clasts of diabase and basalt up to several meters in size. In the Geysers area, this lithofacies is restricted to local meter-sized intercalations composed of sub-rounded clasts, mostly under 0.15 m in size, within finer-grained facies (fig. 10C).

Elsewhere at Wilbur Springs (figs. 5B, 7, log 9) the basal several meters of the succession, overlying mafic ophiolitic volcanics, is composed of well rounded pebbles of basalt, up to 3 cm size; pink micritic limestone, up to 5 cm size, and sub-rounded lithoclasts of volcanioclastic
Fig. 10. Field photographs. (A) Near basal ophiolite-derived breccia, very angular clasts of basalt, diabase, and gabbro cemented by sparry calcite, Digger Creek; (B) angular clasts of vesicular basalt pillow in breccia, Digger Creek; (C) Mainly diabase-derived pebblestone; sub-rounded clasts in a weathered sand matrix; road to the Geysers, near Cold Creek; (D) conglomerate in the transitional unit. Quite well rounded pebbles and cobbles of ophiolite derivation in a muddy matrix, Pope Creek.
Fig. 11. Field photographs: (A) matrix-supported ophiolite-derived rudite, Crowfoot Point, Paskenta area; (B) ophiolite-derived conglomerate, top of the breccia unit succession in the South Fork of Elder Creek, includes abundant gabbro; (C) unconformity between the ophiolite-derived rudites and mudstones marking the base of the Great Valley sequence, South Fork of Elder Creek; (D) ophiolite-derived sand several centimeters above the unconformity shown in (C) same locality.
sandstone up to 45 cm size, within a matrix of reworked volcanic glass, palagonite, basaltic sand, and fine rudite. Marked local lateral thickness and facies variation are observed within single depositional units. For example, traced eastward several hundred meters along the lava-sediment unconformity (fig. 5B), the basal rudite coarsens and thickens, passing into clast-supported breccia, with up to meter-sized detached blocks.

**Matrix-supported conglomerate and breccia.**—Matrix-supported rudite is locally abundant in the Paskenta area, at Crowfoot Point (figs. 6, 7, log 12). Poorly consolidated matrix-supported rudite, up to 6 m thick, is interbedded with mudstone. Clasts are mainly subangular to angular, typically tens of centimeters to locally meter-sized or larger (fig. 11A). The matrix is reddish and purple silty mudstone. Clast composition in individual depositional units varies from nearly monomict (gabbro-rich) to polymict, with lava, diabase, gabbro, and rare smaller clasts of serpentinite. Individual rudite locally rests on siliceous mudstone with an erosive contact. Several kilometers northward, in the upper levels of the succession in Digger Creek (figs. 6, 7, log 14), well exposed matrix-supported rudite alternates with sandstone and mudstone. Individual rudite beds are up to 5.5 m thick; several are amalgamated, for example, with up to four about 0.35 m-thick intervals composed of massive rudite with a mudstone matrix. Clasts are mainly sub-rounded, mainly composed of basic lava, diabase, and gabbro. Upsection the thickness and clast-size of the rudites decreases on average. The final rudite, 0.5 m thick, is nearly massive with angular to sub-rounded clasts, mainly less than 0.13 m in size. Several rudite horizons grade up into turbiditic sandstone and mudstone (see below).

Elsewhere, at Wilbur Springs (figs. 5B, 7, log 11), mudstone and sandstone about 30 to 90 m above an ophiolitic extrusive basement contain lenses of basalt-derived rudite in a muddy matrix. Detached pillow lava blocks, up to several meters in size, pass laterally into lava rubble preserving locally intact pillows floating in mudstone.

**Sandstone.**—Coarse- to locally fine-grained sandstone and siltstone are a subordinate lithofacies in the breccia unit. On the road to the Geysers (figs. 4A, 7, log 6; 13C) thin basal breccias are overlain by up to about 150 m of well indurated sandstone with local outsize diabase blocks. Up section, medium- to thick-bedded nearly massive, medium-grained, sandstone is interbedded with mudstone and rare white siliceous volcaniclastic siltstone (tuffs), passing into rudite (see above), then a fining-upward succession of well stratified fine- medium- and coarse-grained sandstone interbedded with greenish and purple mudstone. Farther south, on the lower slopes of Black Mountain (fig. 4A), by contrast, almost the whole of the breccia unit succession is composed of about 150 m of nearly massive thick-bedded sandstone with subordinate interbedded mudstone, rudite, and pale siliceous volcaniclastic sediments. Elsewhere, the lower part of the succession at Mt. St. Helena (figs. 4B, 7, log 3) is dominated by varicolored red, gray, brown,
medium- to thick-bedded, coarse-grained, massive sandstone. Some horizons are lenticular over several meters laterally. Thick-bedded massive gray sandstone locally grades into fissile gray mudstone. Beds of poorly sorted coarse-grained sandstone, up to several meters thick, are interbedded with rudite higher in the succession (see above). At Wilbur Springs, planar-bedded volcanioclastic sandstone and mudstone dominate the upper part of the breccia unit (figs. 5B, 7, logs 9, 10, 11; 13D, E, F).

In the Paskenta area (figs. 6, 7, log 14; 12A, C), the upper 150 m of the succession includes numerous, up to meter-thick, interbeds of lenticular, coarse- to fine-grained, thin- to thick-bedded, locally amalgamated, sandstone, exhibiting grading, rare micro-cross-lamination, and mudstone rip-up clasts. Complete Bouma Ta-e and Td-e intervals (and combinations) are present (Bouma, 1962). Several matrix-supported rudite beds grade up into turbiditic sandstone, then into laminated siltstone and mudstone. Black and green, graded, finely laminated mudstone occurs as partings. At Crowfoot Point (fig. 7, log 12), medium-bedded intercalations of coarse-grained, massive, almost monomict, serpentinite-derived grit are also present in the breccia unit.

Mudstone.—Mudstone occurs locally as discrete interbeds, as interstitial sediment in rudite, and rarely as thicker intervals. In the upper levels of the succession at Digger Creek (figs. 6, 7, log 14), brown-weathering mudstone and siltstone laminae are interbedded with coarser-grained facies. At Crowfoot Point (figs. 6, 7, log 12) intercalations of purple siliceous mudstone, up to 0.25 m thick, occur between rudite horizons. Elsewhere in the Paskenta area, the matrix is commonly reddish volcanioclastic and siliceous mudstone. In Digger Creek, blocks of diabase and lava breccia locally contain interstitial red siliceous mudstone. Brown and gray finely-laminated mudstones occur in the lower part of the Mt. St. Helena succession, as up to meter-thick intercalations. Pale siliceous volcanioclastic, tuffaceous, siltstone is abundant toward the top of the Geysers road succession (figs. 4A, 7, log 5). Greater thicknesses of mudstone (tens of meters) occur in the upper part of the Wilbur Springs succession, interbedded with sandstone and minor rudite (figs. 5B, 7, logs 9, 10, 11).

**Petrography of the Breccia Unit**

Sandstone composition generally corresponds to the lithology of the local ophiolitic basement (tables 1–6). For example, at Harbin Springs (fig. 4C), the sandstone above gabbroic basement consists almost entirely of angular gabbro grains. Stratigraphically higher sandstone in this succession is polymict, with abundant glassy tholeiitic basalt. At Mt. St. Helena (table 2) sheared gabbro is overlain by sandstone composed almost entirely of kaolinized and chloritized gabbro, but compositions become more heterogeneous up-section. In the Paskenta area, sandstone high in the breccia unit succession (Crowfoot Point, fig. 6) was derived from all levels of the ophiolite stratigraphy, but great composi-
Fig. 12. Photomicrographs and a negative print of a thin section: (A) typical mainly basalt-derived fine rudite, breccia unit, Crowfoot Point, Paskenta area; (B) unusually fresh sub-rounded grains mainly composed of basalt and vesicular altered volcanic glass with a sparry calcite matrix, transitional unit, Mt. St. Helena succession (A–B photomicrographs); (C) graded volcaniclastic sandstone above laminated finer-grained ophiolite-derived silt, Crowfoot Point, Paskenta area (negative print of thin section).
Table 1
Successions on the road to Geysers (see fig. 7, logs 4, 5, 6); number of sections = 6

<table>
<thead>
<tr>
<th>Unit</th>
<th>Generalized lithology</th>
<th>Petrographic summary</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>GVS</td>
<td>Mainly mudstone</td>
<td>Sandstones contain flattened chlorite-replaced radiolarians, angular volcanic quartz,</td>
<td>Reworked local ophiolite-derived acid volcanic grains and pelagic sediment.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>silicified volcanic grains, meta-chert, plagioclase, rare chloritized</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>grains, clinopyroxene, altered basalt, biotite, ophiolite-derived siltstone,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>devitrified acidic glass.</td>
<td></td>
</tr>
<tr>
<td>TRITR</td>
<td>Siliceous mudstone, siltstone, and fine-grained sandstone.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRANS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAGA</td>
<td>Crudeley stratified sandstones, conglomerates, and breccias</td>
<td>Sandstone near top of the succession is well sorted with angular sub-rounded grains of</td>
<td>Upper part of succession mainly derived from upper (extrusive ophiolite) levels with</td>
</tr>
<tr>
<td>BRDCC</td>
<td>grading down into nearby massive homogeneous ophiolite-</td>
<td>plagioclase, aphyric basalt, mudstone intraclasts with traces of radiolarians, and</td>
<td>increased input from local submarine diabase fault scarp near base—relatively “distal” talus fan accumulation. Fault exposure of</td>
</tr>
<tr>
<td></td>
<td>derived sandstone and sub-ordinate rudite.</td>
<td>rare serpentinite.</td>
<td>sheeted sill complex on sea floor.</td>
</tr>
<tr>
<td>CRO</td>
<td>Diabase of sheeted sill complex.</td>
<td></td>
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</tbody>
</table>
**Table 2**

*Successions in the Mt St Helena area (see fig. 7, log 3); number of sections = 8*

<table>
<thead>
<tr>
<th>GVS</th>
<th>Generalized lithology</th>
<th>Petrographic summary</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Siliceous mudstone, sandstone, and conglomerate with locally very well rounded clasts in a reddish siliceous mudstone matrix, some beds are lenticular, rare elliptical carbonate concretions.</td>
<td>Sandstones consist of glassy basalt, pelagonite vesicular basalt, spherulitic devitrified volcanic glass, chloritized glass, minor diabase, plagioclase, augite, vesicular acidic glass, volcanic quartz, biotite, serpentine, quartzose, chert, micritic limestone with calcite-replaced radiolarians, siltstone, intraclasts, and radiolarians. One sample is almost all gabbro and diabase-derived plus ferruginous and siliceous mudstone intraclasts. Siliceous mudstone interbeds are composed of fine-grained pyritic ophiolite-derived siltstone.</td>
<td>Extensive reworking of locally derived top of ophiolite succession (basalt-micritic limestone) mixed with reworked tuff of mainly acidic composition. Pauses in deposition allowed siliceous mud accumulation from suspension; diagenetic reducing conditions.</td>
</tr>
<tr>
<td>B</td>
<td>Very altered nearly massive breccias grade down into conglomerates, sandstones, and mudstone depositionally overlying sheared gabbro; sequence above, cut by dikes or sills.</td>
<td>Toward the base of the succession sandstone interbeds consist of unsorted angular grains of gabbros and little else. Feldspar is altered to kaolinite and ferrogneiss to uralite and chlorite.</td>
<td>Near the top breccias shed from various ophiolite levels, but near the base mainly from local gabbroic basement. Overall coarsening-upward implies continued tectonic activity on seafloor fault scarps.</td>
</tr>
</tbody>
</table>
### Table 3

*Successions in the Anderson Springs-Harbin Springs area (see fig. 7, logs 1, 2); number of sections = 7*

<table>
<thead>
<tr>
<th>Generalized lithology</th>
<th>Petrographic summary</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbiditic mudstone.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fissile mudstones and rare sandstones and basalt/diabase-derived grits, interbedded with fine grained white tuffs and tuffaceous sandstones and massive tuff, locally cross-bedded, laminated reworked tuff directly underlies breccias.</td>
<td>1. Cherty white siltstone consist of tiny volcanic quartz shards, with a chloritic matrix. Radiolarians replaced by drusy quartz and/or fine chaledonic quartz.</td>
</tr>
<tr>
<td>BRE  C CIA  A</td>
<td></td>
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<tr>
<td></td>
<td>Thick sequence of mainly diabase-and basalt-derived massive and crudely stratified breccias, becoming increasingly rich in gabbro downward, locally monomict.</td>
<td>2. Flinty vitreous tuff, entirely fine-grained, with no radiolarians (? dacitic tuff).</td>
</tr>
<tr>
<td></td>
<td>Interbedded sandstones contain gabбро, minor serpentinite, diabase, basalt, and rare recrystallized limestone clasts. Basalt is commonly glassy tholeiite. Where present matrix is ferruginous silt. Basal breccias almost entirely gabброic, lithology similar to underlying gabброic rocks.</td>
<td>3. Pumiceous tuff with altered glass shards, micro-lites of plagioclase, minor pyroxene, and rare quartz; smectite-replaced pumice lapilli.</td>
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<tr>
<td>CRO Gabbros and gabbro pegmatites.</td>
<td>4. Volcaniclastic sandstone with basalt, plagioclase, common volcanic quartz, rare hornblende in a silty matrix with abundant chlorite.</td>
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</table>
**Table 4**

*Successions at Pope Creek (see fig. 7, log 8); number of sections = 11*

<table>
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<th>Unit</th>
<th>Generalized lithology</th>
<th>Petrographic summary</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thin (2 m) conglomerate with some rounded pebbles in a muddy matrix.</td>
<td>Clasts of basalt and gabbro, plagioclase grains; extensive albization of basal mudstone.</td>
<td>Talus fans shed from subjacent submarine fault scarps and mixed with lithics from nearby blocks of higher ophiolitic units. Extremes pressure welding of breccia clasts.</td>
</tr>
<tr>
<td>TRO</td>
<td>0 to 100 m of crudely stratified lenticular ophiolite-derived breccias with outsize blocks of mainly gabbroic and diabasic sheeted complex.</td>
<td>1. Intrusives: gabbro, diabase, olivine gabbro, norite, diorite with plagioclase, pyroxene, iron oxides, olivine; pyroxene uralitized and chloritized; plagioclase replaced by zeolites and phrenite.</td>
<td>Progressively disintegrated, sheared, parent fault scarp exposed composed of sheeted intrusive complex.</td>
</tr>
<tr>
<td>ANS</td>
<td>Transition to sheared and brecciated, then in situ, gabbro-diabase sheeted complex below.</td>
<td>2. Volcanics: porphyritic and vesicular basalt with phenocrysts of plagioclase, pyroxene, olivine, and Na-plagioclase replaced by zeolites, phrenite, and calcite. Pyroxenes altered to chlorite and actinolite-tremolite. Groundmass is divitrified glass, albite. Pyroxene microlites, Fe-oxides; amygdales chlorite-filled.</td>
<td></td>
</tr>
</tbody>
</table>
TABLE 5

*Successions near Wilbur Springs (see fig. 7, logs 9, 10, 11); number of sections = 9*

<table>
<thead>
<tr>
<th>Unit</th>
<th>Generalized lithology</th>
<th>Petrographic summary</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>GVS</td>
<td>Thick classical turbidites.</td>
<td>The breccia lens is composed of mainly zeolitized dark silicified basalt (diabase and microgabbro clasts seen in the field also).</td>
<td>Deep sea turbidite cover.</td>
</tr>
<tr>
<td>B</td>
<td>Mudstones and sandstones pass down into lenticular ophiolite-derived breccias, then into around 80 m of mudstones, sandstones, and lenticular rudites, in turn underlain by nearly massive conglomerate with well rounded clasts.</td>
<td>Course sandstone near base of succession comprises: basalt (glassy and crystalline), chloritized glass, devitrified glass, vesicular glass, pelagonite acidic extrusive rock grains, volcanic quartz, devitrified acidic glass, clinopyroxene, orthopyroxene, hornblende, zoned plagioclase crystals, perthite, diabase, chert, siltstone, micritic limestone, radiolarian chert, patchy calcite cement and chlorite.</td>
<td>Tilting of ocean floor, erosion of inferred former deep sea sediment cover and current redeposition; tectonically-controlled tilting and redeposition increases up section.</td>
</tr>
<tr>
<td>R</td>
<td>C</td>
<td></td>
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<tr>
<td>E</td>
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<tr>
<td>C</td>
<td>I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Pillow basalt, lava breccias, and hyaloclastite with interlava Fe-rich radiolarian chert and rare limestone.</td>
<td></td>
<td>Ophiolitic lavas erupted on irregular ocean floor with background radiolarian pelagic sediments.</td>
</tr>
</tbody>
</table>
Table 6
Successions in Paskenta area (see fig. 7, logs 12, 13, 14, 15); number of sections = 13

<table>
<thead>
<tr>
<th>Unit</th>
<th>Generalized lithology</th>
<th>Petrographic summary</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>GVS</td>
<td>Turbiditic mudstones, siltstones and sandstones, passing down into basal lithoclastic sandstones with interbedded ophiolite-derived rudites.</td>
<td>Sandstones contain basalt, palagonite, diabase, gabbro, plagiogranite, recrystallised chert, meta-chert, serpentinite, perthite, polycrystalline quartz, volcanic quartz, pyroxene, zones plagioclase biotite, rare large chlinoite grains, chlorite, mudstone and siltstone intraclasts, radiolarian, partly recrystallised pelagic sediment, crystalline limestone.</td>
<td>Blanketing by far-travelled turbidites of mainly volcanic arc provenance.</td>
</tr>
<tr>
<td>TRAN</td>
<td>Coarsening-downward oligomict breccia, sandstone, clast- and matrix-supported conglomerate derived from all parts of an ophiolite succession, including large detached blocks of bedded radiolarian chert. Basal horizons include mega-breccias with blocks of basic lava breccia and andesite.</td>
<td>The top 10 m of the breccia unit contains serpentinite, plagiogranite, gabbro, diabase, meta-chert, polycrystalline quartz, hornblende, augite, plagioclase (phenocrysts), volcanic quartz, chert, partly recrystallised pelagic sediment. Feldspar very altered to kaolinite, common secondary calcite and blue chlorite. Ferruginous silty matrix. Ferromagnesian uraltitzed.</td>
<td>Generally fining-up series of overlapping submarine talus fans shed from active fault scarps.</td>
</tr>
<tr>
<td>BREC</td>
<td>Typical breccia is polymict with variable content of very angular unsorted grains of basalt, diabase, gabbro, serpentinite, recrystallized radiolarian chert, also augite, orthopyroxene, altered plagioclase, hornblende, plagiogranite. Clasts commonly largely replaced by calcite and/or chlorite.</td>
<td></td>
<td>Deposited mainly by rock fall, gravity sliding, debris-flow, and minor turbidity currents and suspension accumulation in oxidising deep ocean setting.</td>
</tr>
<tr>
<td>CRIA</td>
<td>Irregular normal contact with ultramafics (wehlite) below.</td>
<td></td>
<td>Major faulting exposed deep ophiolitic levels along submarine fault scarps.</td>
</tr>
</tbody>
</table>
tional variations exist locally between individual beds. Common volcanic quartz and dacitic grains in this area and at Harbin Springs (fig. 13B) confirm the importance of intermediate and silicic, as well as basic, igneous provenance. In general, gabbro and diabase in the sandstones have often disintegrated into component crystals (fig. 13A), whereas the basalt is preserved mainly as lithoclasts. At Wilbur Springs the basal sandstone, unconformably overlying basaltic lava, contains abundant volcanic quartz, silicic tuffaceous sediment, and other grains that are exotic to the local ophiolite basement. Grains are occasionally sheared, recrystallized, or cataclastically deformed; for example, gabbroic grains near the contact with gabbro below in the Harbin Springs remnant (fig. 4C; fig. 7, log 2).

The petrography of the fine-grained sediments of the breccia was not studied in detail. Most mudstones (Digger Creek, Paskenta area, fig. 6) consist of fine-grained ophiolite-derived detritus with scattered radiolarians which are rarely well preserved. Recrystallized radiolarian chert from Crowfoot Point (table 6) is very similar to red chert interbedded with the Coast Range ophiolitic lavas, as exposed at Wilbur Springs (table 5). Sandstone low in the breccia unit at Harbin Springs (table 3) locally contains grains of partly recrystallized micritic limestone. Similar limestones are known from the base of sedimentary successions locally overlying the central Coast Range Ophiolite remnants at several localities (for example, Quinto Creek, Robertson, 1989). Red ferruginous muds and hydrothermal calcite spar also occur in between breccia clasts in large detached blocks, exposed by Digger Creek (fig. 6).

Breccia Unit Deposition

All levels of the ophiolite basement, from the basic extrusives down to the ultramafics, were exposed to seafloor erosion by pervasive faulting. Ophiolite-derived talus was shed from a series of rugged submarine fault scarps. The mega-breccia is indicative of drastic collapse and mass-wasting of steep fault scarps. Tectonic breccia was initially created along active faults, then exposed to erosion on submarine scarps. At Pope Creek, for example, individual fractured sheeted dikes were eroded from the steep, exposed unconformity surface along chilled margins to form several-meter-long intact slabs, some of which then fell into the overlying breccia as outsize blocks (fig. 14). In the Paskenta area, up to tens-of-meter-scale blocks of extrusive and intrusive ophiolitic rocks are interpreted as submarine slumps, involving shear failure accompanied by rotation along discrete shear planes, and are not in situ lava flows, as previously mapped. For example in the South Fork of Elder Creek, thin units of pillow breccia interstratified with sedimentary rudites (Blake and others, 1987a) could not be traced any distance laterally and are reinterpreted as slide blocks. In the Digger Creek area, lava mainly slumped first, then gabbro and diabase blocks slid in and are exposed higher in the succession. At Wilbur Springs, masses of pillow lava slumped and jumbled into individual pillows during downslope
Fig. 15. Photomicrographs: (A) basal gabbro-derived fine rudite, Anderson Springs-Harbin Springs ophiolite remnant. Note sutured grain contacts; (B) volcaniclastic sandstone very rich in vesicular acid volcanic glass (clear) and altered volcanic glass (uniform gray), upper part of Anderson Springs-Harbin Springs succession; (C) volcaniclastic sandstone composed mainly of glassy basalt lithoclasts, upper part of the road to the Geysers succession; (D) volcaniclastic sandstone composed mainly of basaltic lithoclasts, Wilbur Springs remnant; (E) reworked siliceous crystal tuff composed mainly of zoned plagioclase crystals in a sparry calcite matrix, Wilbur Springs succession; (F) reworked siliceous tuff mainly composed of hornblende phenocrysts (right) and angular quartz grains (lower left), Wilbur Springs remnant.
Fig. 14. Inferred fault-scarp features: (A) initial shearing and fragmentation during crustal extension to form seafloor fault scarps; (B) large detached blocks of sheeted dike rock eroded and fell into submarine scree, fissures were infilled with immature talus; (C) talus fans lapped over inactive fault scarps. Based on Pope Creek exposures.

gravity transport. In the Paskenta area, some metric-scale blocks locally preserve an almost undisturbed internal stratigraphy including pillow lava and interbedded ribbon chert, suggesting an origin as submarine slides or glides rather than slumps, in which more internal disruption normally takes place. Where submarine slopes were steep and tectonically active, extensive downslope creep may have occurred, although this is not easily confirmed.

The immature clast-supported breccia was shed from rapidly eroding submarine fault scarps to form lenticular and/or tabular talus wedges (fig. 15). These submarine scree mainly formed by a process of rock fall, defined as freefall, and rolling of blocks and clasts with little internal deformation of clasts. In some cases the talus was apparently almost entirely derived from local small fault scarps, as at Pope Creek, while elsewhere considerable clast-type mixing took place, particularly on major submarine fault scarps, as in the Paskenta area. The persistence of uniform sized clast-supported breccia throughout the breccia unit succession, as at Pope Creek, suggests that steep submarine slopes were maintained during accumulation of the breccia unit, possibly in response to continued faulting and steepening of the basement. Where only thin, but very very coarse, conglomerates are present, as in the South Fork of Elder Creek, much sediment bypassing of upper slope areas may have taken place. Locally (Geyser's road), basal clast-supported breccia is overlain by finer-grained facies, possibly reflecting progressive denudation of the submarine topography after local faulting ended.

The more mature clast-supported breccia presumably records extensive mechanical abrasion during gravity transport, possibly result-
ing from repeated resedimentation due to gravity and/or tectonically-induced slumping and rock-fall, debris-slides (where clasts slide, roll, and bounce), and matrix-poor debris flows (Lowe, 1982). These conglomerates are commonly polymict, reflecting mixing of different clast populations during transport, as exposed at Harbin Springs and in the upper levels of the succession at Digger Creek. Locally, as seen near the base of the Mt. St. Helena succession, small volumes of breccia and conglomerate were reworked as lenses within mainly sand and mud deposits. This may reflect either fault reactivation of the source area and/or a switch in sediment input paths.

Debris flows formed, particularly where volumes of fine-grained argillaceous sediment was available to facilitate plastic flow, clast buoyancy, and a matrix strength support mechanism (Walker, 1975; Middleton and Hampton, 1976; Lowe, 1982). Debris-flows, as exposed in Digger Creek, Paskenta area, apparently resulted from initial sediment build-up, mainly by rock fall and slumping. Gravity and/or tectonically induced oversteeping then resulted in repeated slope failure, mobilizing debris flows, which then moved onto the finer-grained more distal parts of the talus deposits (Hampton, 1972). Slumping also resuspended sand and mud, giving rise to turbidites and to gravity-accentuated grain flows, defined as turbidites with debris flow bases (Walker, 1979).

Sand and mud predominated in areas of more subdued seafloor relief, as at Wilbur Springs, where the breccia unit overlies ophiolitic lava with only a low-angle unconformity. Oxidative weathering of ophiolitic rocks exposed on the seafloor liberated reddish ferruginous
mud, for example at Mt. St. Helena and on the road to the Geysers. Some fine-grained sediment also may be “rock flour” milled along fault scarps, then eroded. Sheared, recrystallized, and cataclastic grains attest to this process. True pelagic chert is occasionally observed in the interstices between breccia clasts (for example, in Digger Creek). This sediment apparently percolated into cracks when the breccia was still attached to parent fault scarps and was later preserved as detached blocks within the breccia unit. Small volumes of silicic volcanlastic sediment on the road to the Geysers area was identified as pyroclastic (airfall) tuff on the basis of the occurrence of angular β quartz phenocrysts, devitrified volcanic glass shards, and silicic lithoclasts. The tuff is variably admixed with reworked ophiolitic material.

**Transitional Unit**

The transitional unit is located between the breccia unit and the Great Valley Group and consists of 0 to 10 m of siliceous mudstone, sandstone, and minor volumes of conglomerates, with locally well-rounded clasts. The transitional unit locally contains reportedly lower Tithonian (zone 3) radiolarians in green and gray volcanlastic sediments and grades into mudstone of the “Knoxville Formation,” for example, in the Wilbur Springs area (E. A. Pessagno Jr, in Hopson, Mattinson, and Pessagno, 1981). In the South Fork of Elder Creek (figs. 6, 7, log 15) the transitional unit is restricted to several centimeters of dark gray siltstone overlying conglomerate clasts along a sharp, irregular, unconformity surface below the Great Valley Group (fig. 11C). Several en echelon lenses there are composed of coarse-grained ophiolite-derived sandstone (fig. 11C), up to 2.5 m long by up to 0.23 m thick. Similar thin lenses of ophiolite-derived sandstone and fine rudite (clasts <1 cm) persist tens of meters higher in the succession (fig. 11D). Farther south, at Crowfoot Point (figs. 6, 7, log 12), the highest levels of conglomerate in the breccia unit pass directly into the transitional unit composed of several meters of ophiolite-derived sandstone and siltstone with a 2.2 m-thick rudite intercalation containing gabbro clasts up to 10 cm in size. Elsewhere, at Harbin Springs (figs. 4C, 7, log 1), the breccia unit is overlain unconformably by up to several tens of meters of pale silicic volcanlastic, tuffaceous, siltstone with local lenses of ophiolite-derived rudite near the base of the Great Valley Group (McLaughlin and Pessagno, 1978).

At Mt. St. Helena (figs. 4B, 7, log 3: 12B) the breccia unit is overlain by about 5 m of siliceous mudstone, sandstone, and rudite with a muddy matrix, together with scattered carbonate concretions. Numerous well-rounded clasts up to 0.35 m in size are mainly composed of vesicular basalt and diabase in a greenish or reddish siliceous mudstone matrix. Interbedded sandstone is silica-cemented. The greenish gray, finely-laminated, siliceous siltstone and mudstone exhibit parallel-lamination, local micro-cross-lamination, and small-scale soft-sediment disruption features. On the road to the Geysers (figs. 4A, 7, logs 5, 6),
the transitional unit succession (about 10 m thick) consists of rudite with scattered rounded clasts near the base, passing up into alternating well-cemented medium- to thick-bedded sandstone, dark greenish-gray siliceous mudstone, millimeter-thick lenticular siltstone laminae, and homogeneous and siliceous mudstone. Elsewhere, at Fir Creek (figs 5D, 7, log 7) the breccia unit is overlain by up to 2 m of relatively texturally-mature calcite-cemented polymict conglomerate with a coarse sandstone matrix. Similarly, at Pope Creek (figs. 5C, 7, log 8) a 2 m thick transitional unit consists of polymict conglomerate with relatively well rounded clasts in a matrix of khaki-colored graywacke and mudstone of the overlying Great Valley Group (fig. 10D).

Petrography of the transitional unit.—The composition of the transitional unit (tables 1–6) tends to reflect that of the breccia unit below. Well-cemented transitional unit sandstone commonly contains unaltered chemically unstable grains (ferromagnesian minerals). A good example is at Mt. St. Helena (table 2), where the breccia unit below is extremely altered, while sandstone of the transitional unit above contains abundant rounded grains including very finely crystalline basalt, vesicular, phryic, and aphyric basalt, palagonite, and devitrified spherulitic volcanic glass. In addition, there are grains of large, clear, volcanic quartz with embayed margins and tiny microlites, very strongly zoned tabular plagioclase crystals, hornblende, large unstrained tabular biotite crystals, and lithoclasts of recrystallized silicic extrusive rocks. Sedimentary rock fragments are represented by micrite, recrystallized limestone, radiolarian mudstone, variably recrystallized radiolarian chert, as well as intraformational mudstone rip-up clasts. The polycrystalline quartz is identified as mainly recrystallized chert and devitrified silicic volcanic glass.

Although not studied in detail, in general, mudstone in the transitional unit consists of tiny angular quartz and plagioclase grains and scattered calcite-replaced radiolarians. Some siliceous mudstones are packed with poorly preserved, often chloritized, flattened, radiolarians (on the Geysers road), with locally abundant diagenetic pyrite, as at Mt. St. Helena.

Interpretation of the transitional unit.—The transitional unit, like the breccia unit below, was mainly derived from the ophiolitic basement. However, compositions are commonly more heterogeneous, with numerous siliceous volcanic and volcaniclastic grains of rocks not exposed in the ophiolite. Very local silicic clasts in the breccia unit (Paskenta area) were interpreted above to indicate proximity of a concealed volcanic arc. The silicic grains in the transitional unit presumably had a similar source, implying that an arc complex existed more regionally.

A puzzling aspect of the transitional unit (and locally the breccia unit also), for example, at Pope Creek, Fir Creek, and Mt. St. Helena, is that clast rounding is not easily envisioned purely as the result of reworking by traction currents or by gravity. For example, Karson (in
press) notes that on the Clipperton Transform, where extreme gravity reworking of clasts is taking place, clast rounding is not observed. Rounding probably instead took place above the wave base in the transitional unit, but there is no evidence of neritic accumulation or emergence, for example; indeed the mudstone contains abundant radiolarians (for example, Geysers road). The rounded clasts were possibly reworked off topographic highs into deeper water where texturally mature sands were generated by traction currents, as at Mt. St. Helena and on the Geysers road. There is, however, no evidence of pronounced localized uplift (blockfaulting) that would have triggered sediment instability (slumping). The most plausible scenario is that the breccia unit previously accumulated at moderate depths (?<1 km), followed by early Tithonian regional tectonic uplift (and/or eustatic sealevel fall) that elevated topographic highs to within the wave base. Subsidence then ensued, prior to deposition of turbidites at the base of the Great Valley Group (middle-upper Tithonian; see below).

**Base of the Great Valley Group**

Deep-water mudstone, turbiditic sandstone, and minor airfall tuff characterize the Late Jurassic to Early Cretaceous lower Great Valley Group (Bailey and Jones, 1973; Swe and Dickinson, 1970; Dickinson and Rich, 1972; Ingersoll, 1983).

Dating of the base of the Great Valley Group is based mainly on occurrences of the bivalve *Buchia* (B. Piochii, Jones, and Imlay, 1969), radiolarians, and local occurrences of Early Cretaceous belemnites and dinoflagellates. Radiolarians are assigned to a lower Tithonian age (zone 2, subzone 2A; Pessagno, 1976; Pessagno, Blome, and Longorio, 1984). Elsewhere, sparse occurrences of *Buchia* and common radiolarians (data summarized in Hopson, Mattinson, and Pessagno, 1981) indicate Tithonian ages for near basal horizons of the Great Valley Group. Specifically, lower Tithonian radiolarians occur 76 m above the transitional unit at Mt. St. Helena (figs. 4B, 8, iv; McLaughlin and Pessagno, 1978), and middle and late Tithonian *Buchia* ages are reported from Wilbur Springs (figs. 5B, 8, ii; McLaughlin and others, 1985), while elsewhere the basal sediments are apparently middle–upper Tithonian (at Harbin Springs) or Early Cretaceous (on the Geysers road) (McLaughlin and Pessagno, 1978).

In the Paskenta area, turbiditic sandstone first appears near the base of the succession. The existing seafloor topography, dominated by fault scarps, was apparently rapidly smothered with little modification (Crowfoot Point, South Fork of Elder Creek). By contrast at localities farther southwest within the Franciscan Complex outcrop (Harbin Springs, Fir Creek) the base of the Great Valley Group is composed of 10 to 100 m of mudstone before the first appearance of sandstone turbidites. Silicic airfall tuffs are widely distributed as thin intercalations through the thick Late Jurassic basal Great Valley Group successions (Paskenta) and reach thicknesses of about 50 m at the base of successions
elsewhere (Harbin Springs, Pope Creek, Fir Creek). Topographically higher seafloor areas were presumably exposed longest and continued to shed ophiolitic talus in Tithonian time, as exposed at Harbin Springs. The major northwest-southeast trending left-lateral Paskenta Fault zone is attributed to northwest-southeast directed growth faulting before tilting. The probable setting was an actively extending forearc area above an eastward-dipping subduction zone (Suchecki, 1984; Vogel, 1985). Ophiolite-derived debris flows within the basal, Jurassic, part of the Great Valley Group in the Paskenta area were apparently derived from relatively uplifted seafloor areas to the west.

In the vicinity of Lake Berryesa (fig. 5A), serpentinitized ultramafic ophiolitic rocks at the base of the Great Valley Group are depositionally overlain by a Tithonian-aged "chaotic" unit (Phipps, 1984). Phipps described large-scale low-angle sheets of deep-level ultramafic ophiolitic rocks, largely harzburgite tectonite, depositionally overlain by debris flows up to 1 km thick, with a muddy matrix. The debris flows accumulated directly on ultramafic ophiolitic rocks and pass transitionally upward into fine-grained terrigenous sediments higher in the Great Valley Group. For example, these relationships are visible along the road by the northwest shore of Lake Berryesa (fig. 5A). In general, detached blocks in debris flows include all levels of the ophiolite succession, ophiolite-derived clastics, greenschist, and amphibolite-facies, mafic metamorphic rocks (but no blueschists), basalt and radiolarian cherts (MacPherson and Phipps, 1988). The plutonic ophiolitic rock and breccias are similar to the Coast Range Ophiolite and its cover elsewhere, while the basalts, cherts, and metamorphics are comparable with melange lithologies below the Coast Range Ophiolite in the Paskenta area (Round Mountain serpentinite melange: Jayko, Blake, and Harms, 1987).

Elsewhere (Wilbur Springs), the basal, turbiditic facies of the Great Valley Group are interbedded with serpentinitic sandstone and debris flows containing rare clasts of garnet amphibolite, amphibolite, blueschist, greenschist, metachert, and Early Cretaceous fossils (Carlson, 1984a, b, c). During Early Cretaceous time, underlying ophiolitic ultramafic rocks were apparently hydrated and rose along extensional faults as serpentinite diapirs (Carlson, 1984b, c). Similar diapiric serpentinite volcanoes are recorded in the modern Mariana forearc area (Hussong and Fryer, 1982).

Two distinct types of debris-flow were thus generated in a fore arc setting during Tithonian and Early Cretaceous time. At some earlier time (Kimmeridgian, 155 Ma) the ophiolite was disrupted, exposing ultramafic rocks on the seafloor. Facies equivalents of the breccia unit accumulated. The serpentinite-mud matrix debris-flows formed later in Tithonian time, contemporaneously with basal Great Valley Group deposition. Other lithologies in the debris flows, including high-Ti basalt (MacPherson and Phipps, in press), radiolarian chert, amphibolite, and plutonic ophiolitic rocks are interpreted as the result of the
earliest stages of Franciscan subduction-accretion (Jayko, Blake, and Harms, 1987). Slumping was presumably triggered by subduction-related tectonic movements in the fore-arc. Elsewhere (Wilbur Springs) ultramafic rocks were hydrated and protruded up extensional faults, giving rise to submarine serpentinite volcanoes. The presence of entrained clasts of blueschist suggests that Franciscan-type rocks were already assembled beneath the forearc wedge by Early Cretaceous time (Carlson, 1984a, b, c).

In summary (fig. 16), eastward subduction was active during Tithonian-Early Cretaceous time, coeval with basal Great Valley Group deposition. Forearc processes included localized subsidence and growth-faulting, accumulation of talus from surviving seafloor ophiolite highs, serpentinic debris flow deposition, and diapiric serpentinite protrusion. These processes were superimposed on deep-water terrigenous turbiditic and minor tuffaceous input, presumably from the North Sierra and Klamath areas to the east and northeast. With this setting in mind, we now return to the origins of the breccia and the transitional unit.

TECTORIC SETTING OF OPHIOLITE-DERIVED SEDIMENTATION

Suggestions in the past range from models involving thrusting, vertical uplift, erosion of high-standing edifices, and crustal rupture. Blake, Jayko, and McLaughlin (1985) envision thrusting of the ophiolite, followed by erosion of submarine fault scarps. Blake and others (1987) report that upper levels of the pillow lavas, sheeted dikes, and sills and intruding gabbros are thrust imbricated in the Paskenta area. Specifically, near the South Fork of Elder Creek the breccia unit is reported to seal thrusts that place ultramafic ophiolitic rock over gabbro

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Fig. 16. Inferred forearc setting of the Coast Range ophiolite basement in latest Jurassic (Tithonian) and Early Cretaceous time.
and diabase (Blake and others, 1987b). In this model the Paskenta area could be compared, for example, to the Gorringe Bank in the Atlantic; this is believed to be an oceanic fracture zone, now undergoing compression, following initiation of subduction under Iberia (Lagabrielle and Auzerde, 1982: fig. 17D). However, elsewhere there is little evidence of significant folding, contractional faulting, or thrust duplication of the ophiolite succession prior to deposition of the breccia unit.

In the context of a possible compressional setting, the breccia could be compared to ophiolite-derived clastics shed from emplacing ophiolite nappes, for example the Semail ophiolite, Oman. Texturally similar breccias there were shed from fault scarps during the early stages of crustal disruption, associated with emplacement of the ophiolite onto the Arabian continental margin. However, in this case the clasts are almost entirely mafic lava and pelagic sediment, derived from the upper crustal levels of the ophiolite (Robertson and Woodcock, 1983), without common plutonic clasts as in the northern California breccia unit.

Lagabrielle and others (1986) were impressed with the evidence from derived clasts that the Coast Range Ophiolite formed part of an arc complex and suggested the breccia resulted from uplift and erosion of the arc flanks, triggered by the Nevadan orogeny. Arcs are composed of thickened crust and thus kilometer-deep erosion is implied to reach plutonic rocks. Phipps (1984) suggested the Coast Range Ophiolite was uplifted and deeply eroded related to a “wave of uplift,” contingent on flipping of a west-dipping subduction zone and onset of eastward Franciscan subduction. Simple uplift and deep erosion are, however, hardly tenable in view of the lack of evidence of general subaerial exposure, shallow water facies, or neritic fossils.

Other workers have favored tensional settings, at least implicitly. Hopson, Mattinson, and Pessagno (1981) concluded that the ophiolitic breccias record disruption and uplift of oceanic crust, giving rise to talus deposits associated with submarine fault scarps. Harper, Saleeby, and Norman (1985, p. 285) suggested an intra-oceanic transform fault origin, a view also shared by Blake and others (1987a). MacLaughlin and Ohlin (1984) note that many ophiolite units are separated by low-angle faults causing great disruption, for example, in the Clear Lake area. The writer stresses that the field relations are compatible with a model of early deformation of the ophiolite involving pervasive tension that exposed all levels of the ophiolite to erosion on the seafloor. This style of deformation is similar to that of rifts, for example, the continental Basin and Range (Profett, 1977; Wernicke and Burchfiel, 1983; Gibbs, 1984). Indeed, the ophiolite-derived breccias are similar to talus shed from submarine fault scarps in a range of tensional, modern oceanic, and ancient ophiolitic settings (fig. 17A, B).

Data from modern oceanic crust suggest that rifted ridge (Karson and Dick, 1983; Karson and others, 1984: fig. 17A) and transform settings could be homologous with the breccia unit. Submersible work suggests that slow spreading ridges with limited, episodic, magma supply
Fig. 17. Some theoretically possible, but unsatisfactory, tectonic settings for accumulation of the North California ophiolite-derived breccias: (A) at a rifted spreading ridge; (B) in an active fracture zone formed at a rifted spreading axis; (C) on the trench-slope break within a forearc area; (D) along a deformed, previously inactive, fracture zone formed at a rifted spreading axis (data sources are specified in the text).
undergo pervasive extension and detachment faulting at various levels beneath the floor of the median valley, for example in the Mid Atlantic Ridge at the Kane Fracture Zone (Barany and Karson, 1989). Tensional faulting is the main means of exposing ultramafic and gabbroic rocks on the ocean floor. In an ophiolite the vertical succession expected for this model would comprise sheared plutonic rocks, overlain by breccia, intruded by gabbroic rocks, and then overlain in turn by basalts and pelagic sediments. Close comparisons can indeed be drawn with the Jurassic Apennine ophiolites (Lemoine, Tricart, and Boillot, 1987), interpreted by Cortesogno and others (1980) as having formed along fracture zones, and by Barrett and Spooner (1977) as representing rifted spreading ridge segments. The extrusives there directly overlie plutonic rocks (gabbros), while associated breccias are interbedded with basic extrusives, localized hydrothermal sulfide, and manganese deposits. However, more of these features are similar to the north California breccia unit.

Where long ophiolitic successions are preserved in northern California (South Fork of Elder Creek; Geysers area) an ideal, complete, ophiolite succession is apparently present, including a well developed sheeted diabase complex. This contrasts apparently with modern slow-spreading, rifted, mid ocean ridges (Karson and Dick, 1983; Karson and others, 1984). Also, the geochemistry of the ophiolitic lava suggests an above subduction zone, rather than mid-ocean ridge setting. Indeed, the paucity or absence of extrusive and intrusive rocks within the breccia unit opposes any active spreading setting.

An alternative is that the Coast Range Ophiolite and the breccia unit formed in an oceanic fracture zone setting (fig. 17B). Harper, Saleeby, and Norman (1985), for example, mention the north California breccias in passing and suggest that the Coast Range Ophiolite and its counterpart, the Josephine ophiolite, farther north, formed at spreading centers, offset by long transform faults. Modern transform faults (Bonatti, 1976, 1977; Choukroune, Francheteau, and Le Pichon, 1978; Garfunkel, 1981, 1986; Gall and others, 1984) do indeed expose all levels of the oceanic crust and mantle on the ocean floor with talus deposition similar to the breccia unit.

Submersible studies of the fast-slipping (11 cm/yr) Clipperton Fracture Zone (Karson, in press) reveal mainly basaltic talus and finely abraded “rock flour” mixed with minor pelitic carbonate. The talus accumulated as small coalescing fans at the base of steep active fault scarps, just as envisioned in northern California. Features not seen in California, however, include a dominance of basaltic clasts (without plutonics); an abundance of faults and closely spaced fractures in breccia and mudstone; large numbers of deformed clasts (cataclastite, micro-breccia, and protomylonites); and common evidence of sediment erosion and recycling. A vertical succession in such an ophiolite would comprise fractured basaltic basement, deformed breccia and mudstone (the basaltic flows being erupted during passage of the ridge-transform
intersection), and finally, overlying pelagic carbonate. Slow-slipping fracture zones commonly expose plutonic rocks, but, there the breccias accumulate more slowly and are admixed with pelagic carbonate (Karsen, in press), in contrast to the Coast Range breccias.

In the best documented ancient ocean transform, the Arkapas fault in the Late Cretaceous Troodos ophiolite, Cyprus, the strike-slip zone is marked by a severely fractured basement, protrusion of mafic and ultramafic plutonic rocks to high crustal levels, intrusion of dikes sub-parallel to the fault lineament, and accumulation of mainly basaltic talus interbedded with mafic extrusives. This is overlain, in turn by hydrothermal sediments (umbers) and siliceous and calcareous pelagic sediments (Simonian and Gass, 1978; Murton and Gass, 1986; Murton, 1986; Robertson, 1978). In view of these marked differences an oceanic fracture zone origin is not favored for the Coast Range breccias.

Tensional faulting is also documented from modern and ancient forearc and back-arc settings (fig. 17C). However, normal faults in the Mariana forearc appear to be mainly high-angle and of limited throw, less than 250 m (Mrozowski and Hayes, 1980). Metamorphosed breccia clasts were recovered from fault zones in the modern Mariana back arc basin (Hussong and others, 1982) where extension took place in young hot crust. By contrast, the northern California breccia unit experienced only low-grade seafloor alteration, suggesting that this ophiolite was already cold by the time of tensional faulting and breccia formation. Normal faults, similar in scale to the Mariana forearc, also cut the sedimentary cover of a Jurassic arc-ophiolite on Cedros island, Baja California (Busby-Spera, 1988), interpreted as an emplaced back-arc basin (Kimbrough, 1985), but again the scale of these faults is small relative to those inferred in northern California.

By contrast, any interpretation must take account of the relative absence of pelagic sediment between the breccia unit and at the base of the terrigenous Great Valley Group. This implies that the breccia unit accumulated close to a continental margin rather than in an open ocean setting. Conscious of this constraint, MacLaughlin explained the breccia in terms of disruption of ophiolitic crust after docking with the Pacific continental margin. Erosion of submarine highs (MacLaughlin and Pessagno, 1978) or deep ocean fault scarps (MacLaughlin and others, 1985) was envisioned, possibly related to oblique opening of a "marginal" basin (MacLaughlin and Ohlin, 1984), similar to the Gulf of California (Curray and Moore, 1982). The chief problems with this model are the absence of terrigenous sediment within the breccia unit, suggesting separation from, or blocking of, terrigenous input; the presence, locally, of well-rounded clasts, implying some shallow-water influence; and the lack of voluminous submarine volcanism that should inevitably accompany thinning of oceanic crust to near or below the Moho.

Another possibly comparable strike-slip setting is that of ophiolite-derived breccia deposition associated with the emplacement of ophiolites in the Late Cretaceous-early Tertiary Antalya Complex in south-
Fig. 18. Block diagram to illustrate the deposition of the breccia unit as a series of talus wedges shed from submarine fault scarps.

west Turkey. However, unlike the north Californian breccias, these breccias were related to a long history of strike-slip faulting (Robertson and Woodcock, 1980) and are now preserved in sub-vertical fault-bounded slivers within a melange unit.

PROPOSED PLATE TECTONIC SETTING

The deposition of the breccia unit is attributed to crustal tension in and above subduction zone setting, as illustrated in figures 18 and 19. Very similar breccia overlies a Paleozoic arc-ophiolite in Norway (Søre

Fig. 19. Formation of faulted seafloor topography by pervasive crustal extension of already formed, cold, ophiolitic crust.
Lyklingholmen Formation; Amaliksen and Sturt, 1984) and may have a similar origin. In California, the ophiolitic basement was tectonically brecciated and exposed to mass wasting, giving rise to talus wedges at the foot of submarine fault scarps. Derivation from both the hanging-wall and footwall is inferred (for example at Paskenta). The hypothesis of late Mesozoic strike-slip dispersal of the North California ophiolite remnants (McLaughlin and Ohlin, 1984) implies that the crustally extended zone was hundreds of kilometers long or more. Facies trends are mainly sub-parallel to the regional north-northwest-south-southeast structural grain (Paskenta, Harbin Springs, Black Mountain areas), suggesting an originally more north-south than east-west trend for the extensional zone. Some orthogonal high-angle faults (Geyser Peak-Black Mountain; fig. 4A) indeed could be original tension-related transfer faults. The possible polarity of the crustally extended zone can be tentatively inferred from the local facies geometry, as shown in figure 20.

Ophiolite genesis from 169 to 161 Ma Callovian-Oxfordian on the Harland and others (1982) time scale compares with the breccia unit deposition from late Kimmeridgian-Tithonian time (156-144 Ma), suggesting that a 5 to 10 Ma hiatus separated these events. During Kimmeridgian-Tithonian time a volcaniclastic and tuffaceous cover

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**Fig. 20.** Polarity of the major fault scarps: (A) the present field relations at the best exposed area, near Paskenta; (B) assuming an eastward polarity, possible sections (indicated) do not produce the observed successions as in (A); (C) westward polarity. Possible section (indicated) corresponds to the exposed succession. Locally, the basal Great Valley sequence is vertical to overturned; simple correction for tilt also favors (C).
accumulated on the coeval Coast Range Ophiolite in central California (Hopson, Mattinson, and Pessagno, 1981; Robertson, 1989). Similar silicic tuffaceous sediment is locally admixed with ophiolitic detritus above basic extrusives in northern California (Wilbur Springs) and occurs commonly in the overlying transitional unit below the Great Valley Group. Silicic tuffaceous sediment was apparently eroded from a concealed volcanic arc and was initially deposited on the northern California Coast Range Ophiolite, as in central California, but this sediment was apparently later almost entirely removed during the phase of Kimmeridgian-Tithonian tensional faulting that ensued (fig. 21).

Deposition of the breccia unit and the transitional unit were coeval with the Nevadan orogeny (about 155 ± 3 Ma). Robertson (1989) concluded that the contemporaneous, 169 to 161 Ma, central California Coast Range Ophiolite remnants formed above a continentward (eastward) dipping subduction zone as an “arc-ophiolite,” possibly akin to the Eocene Mariana forearc (fig. 22Bi). Continentward subduction eventually swept this “arc-ophiolite” under the Pacific continental margin, possibly triggering the Nevadan orogeny (fig. 22Bii). In an alternative (less favored) model, the Coast Range Ophiolite formed as a marginal ocean basin above a westerly (oceanward)-dipping subduction zone (fig. 22Ai), which later collided with the continental margin (Schweickert and Cowan, 1975: Ingersoll and Schweickert, 1986) (fig 22 AiI). The (Cretaceous-Tithonian) tuffaceous sediments overlying the central California ophiolite remnants are ocean arc-related, whereas Tithonian counterparts at the base of the Great Valley Group presumably have a continental margin origin. In both models a Tithonian Franciscan trench was established beneath the newly docked Coast Range “arc-ophiolite.” The serpentine melange containing basaltic lava, radiolarite, plutonic ophiolitic rocks, and amphibolite blocks, structurally underlying the Coast Range (Round Valley Serpentine Melange; Jayko, Blake, and Harms, 1987), also thick high-Ti basaltic lavas (Stonyford seamount complex; Hopson, Mattinson, and Pessagno, 1981:

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![Diagram](image-url)

**Fig. 21.** Formation of the transitional unit between the ophiolite-derived breccias and the Great Valley Group by reworking of tuffaceous and pelagic sediment derived from the deep water cover of adjacent ophiolitic crust.
Fig. 22. Alternative plate tectonic setting for genesis of the ophiolite-derived breccias of Northern California: (A) related to a flip(? in subduction polarity; (Ai) the Coast Range Ophiolite forms as a marginal basin above a westward-dipping subduction zone; (Aii) crustal tension related to breccia formation, with initiation of eastward (Franciscan?) subduction following collision (Nevadan orogeny); (B) related to only eastward-dipping subduction; (Bi) the Coast Range Ophiolite forms as an intra-oceanic arc-ophiolite complex that collided with America during the Nevadan orogeny. Crustal tension and breccia formation is related to roll-back of the subducting slab resulting in tension within the upper plate. Model B is preferred.

MacPherson, 1983) and melange elsewhere (Mysterious Valley Formation, Lake Berryessa area (MacPherson and Phipps, 1989) are all believed to have been underplated during an early phase of continentward-directed Franciscan subduction-accretion. In addition, blue amphibole within detached blocks in the Franciscan complex, dated 151 to 98 Ma, is believed to record accretion of oceanic crust to the hot hangingwall of the Coast Range Ophiolite during the early stages of Franciscan subduction-accretion (Cloos, 1982).

Following docking with the Pacific continental margin, the Coast Range Ophiolite was stranded in a forearc setting. Strong crustal tension of the ophiolite then occurred as subduction was reorganized, as illustrated in figure 19. Subduction slab-pull is suggested as the major driving force. Subduction of a long dense slab is known to result in oceanward retreat of the subduction zone hinge (Dewey, 1980) and rifting of the upper plate in the Mediterranean, in the Aegean Sea, and the Tyrrenhian Sea (Malinverno and Ryan, 1986). The crustal extension in California could relate to oceanward retreat of the subduction zone, immediately following collision and docking of the “arc-ophiolite” with the Pacific margin of North America. The uplift inferred from the transitional unit could record isostatic rebound and/or uplift related to initial, lower Tithonian, Franciscan subduction-accretion. As eastward subduction became well established terrigenous turbidites then pro-
graded over the disrupted Coast Range ophiolitic forearc, while underplating of Pacific crust (for example seamounts) began.

CONCLUSIONS

1. The Coast Range Ophiolite in northern ophiolite preserves remnants of an originally complete 169 to 161 Ma ophiolite, believed, on the basis of limited available geochemical evidence, to have formed above a subduction zone, like its coeval southern California counterparts.

2. The 0 to 500 m thick breccia unit of Kimmeridgian to Tithonian age at one place or another unconformably overlies all levels of the ophiolite, including mafic lava, a sheeted complex, gabbro, and ultramafic rocks.

3. The formation of the breccia unit is attributed to tectonic faulting near a continental margin in Kimmeridgian-Tithonian time (about 155 Ma), following genesis of the ophiolite (mainly) from 169 to 161 Ma (Callovian-Oxfordian; Harland and others, 1982 time scale).

4. The breccia unit accumulated mainly by rock fall and slumping, with additional sliding, debris flow, turbidity, and traction current deposition, and accumulation of silicic air fall tuff: pelagic sediment is minimal.

5. The breccia unit was mainly derived by local erosion of the Coast Range Ophiolite basement, but locally abundant silicic volcanics were apparently derived from non-exposed arc volcanics.

6. The overlying, 0 to 10 m, thick transitional unit records reworking of the underlying breccia unit, with erosion of exotic silicic tuffaceous sediment derived from a volcanic arc, that was possibly located below the Sacramento Valley to the east. The well-rounded nature of many clasts suggests localized uplift above wave base; evidence of general emergence with neritic deposition is, however, lacking.

7. The overlying Kimmeridgian-Tithonian base of the Great Valley Group formed in a locally tectonic forearc setting coeval with initial accretion of the Franciscan Complex. Pre-existing breccia unit sediments were locally reworked as blocks in serpentine debris flows, while serpentine diapirs protruded through the forearc basement, as in the modern Mariana forearc.

8. The breccia unit can be compared with a range of tectonic settings in modern oceanic crust and ophiolites, but significant differences are apparent. In the favored model, the Coast Range Ophiolite formed above an intra-oceanic subduction zone (169-161 Ma), then collided with the Pacific continental margin of America during the Nevadan orogeny (155 ± 5 Ma). Simultaneously, the trench migrated oceanward, subjecting the newly docked ophiolitic forearc to strong crustal tension. Submarine fault scarps were rapidly eroded, followed by uplift and reworking to form the 0 to 10 m thick transitional unit, then subsidence and deposition of terrigenous turbidites from the Klamath-
Sierra continental margin, marking the base of the Great Valley Group.

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