Early Mesozoic tectonic evolution of the western Sierra Nevada, California

RICHARD A. SCHWEICKERT *Department of Geological Sciences and Lamont-Doherty Geological Observatory of Columbia University, New York, New York 10027*
DARREL S. COWAN *Department of Geological Sciences, University of Washington, Seattle, Washington 98195*

ABSTRACT

Prebatholithic rocks of Mesozoic age in the Sierra Nevada can be interpreted as remnants of ancient volcanic arcs, subduction complexes, and sequences of oceanic lithosphere. Two partly coeval subparallel volcanic arcs, one in the western foothills and the other in the northern and eastern Sierra Nevada, are juxtaposed. The western arc was an east-facing island-arc complex that evolved through a series of steps including formation of a remnant arc and interarc basin. The eastern arc was a west-facing marginal arc that was constructed on the edge of North America. Both arc-subduction complexes consumed intervening oceanic lithosphere and collided during the Late Jurassic Nevadan orogeny. Generation of magmas in both arcs apparently ceased at about this time, and renewed subduction was initiated west of the island arc in latest Jurassic time, giving birth to the Franciscan-Sierran arc-trench complex. Fault zones and mélanges in the western Sierra Nevada reflect the complex suturing at the collision boundary. Pre-Tithonian ophiolite at the base of the Great Valley sequence in the Coast Ranges originated in a back-arc or marginal basin setting with respect to the coeval Sierran foothills arc. *Key words: California, Mesozoic geology, tectonics, Sierra Nevada, igneous rocks.*

INTRODUCTION

Prebatholithic rocks exposed along the western flank of the Sierra Nevada (Fig. 1) can best be characterized as a series of elongate northwest-trending belts separated from one another by major, steeply dipping fault zones. Pioneering mapping by Turner (1893a, 1893b, 1894a, 1894b, 1894c, 1895, 1897, 1898), Turner and Ransome (1897a, 1897b), Ransome (1899), Lindgren (1894, 1900), Lindgren and Turner (1894, 1895), and later Clark (1964) established that each belt contains rocks of different ages, lithologies, and deformational styles. However, a satisfactory hypothesis to account for their origin and juxtaposition has remained elusive.

In accord with plate-tectonics theory, we believe that certain distinctive rock assemblages in the western Sierra Nevada can be interpreted as remnants of ancient volcanic arcs, subduction-zone complexes, and sequences of oceanic crust and upper mantle. Our reconnaissance field work, together with published stratigraphic and structural data, suggests to us that the assemblages record the Late Jurassic collision of an oceanic island arc with a west-facing arc-trench system constructed on the North American continental margin in early Mesozoic time. The purposes of this paper are to outline our model for the tectonic evolution of the western Sierra Nevada, discuss its implications, and more importantly, summarize the critical field data upon which it is based. However, we want to stress that our model, anticipated in some respects by Hamilton (1969) and Moores (1972), is simply a working hypothesis that must be rigorously tested by additional field work.

REGIONAL SETTING

Most rocks older than the Late Jurassic–Late Cretaceous composite Sierra Nevada batholith are exposed in a belt 50 to 80 km wide and nearly 400 km long (Fig. 1). Rocks of the "foothills" or "western metamorphic" belt are overlain unconformably by sedimentary rocks of the Great Valley on the west and are intruded by granitic rocks of the Sierra Nevada batholith on the east. Similar rocks are known from drill-hole and geophysical data to underlie a major part of the Great Valley, but the nature and location of their buried boundary with the Franciscan Complex, widely exposed in the California Coast Ranges west of the valley, are controversial. Scattered granitic, gabbroic, and ultramafic bodies occur within the terrane but are relatively small and areally insignificant when compared to much more voluminous metasedimentary and metavolcanic rocks. Rocks and structures correlative with those in the foothills belt crop out in the Klamath Mountains to the northwest. Highly metamorphosed rocks of Middle Jurassic and earlier ages form pendants in the eastern and southern parts of the Sierra Nevada batholith.

Prebatholithic rocks can be conveniently subdivided into three major lithologic and stratigraphic subprovinces, here informally designated as follows: (1) the predominantly Jurassic "western belt"; (2) the "central belt," probably largely Paleozoic in age; and (3) the "eastern belt," mostly of Mesozoic age but in part containing Paleozoic rocks. Broad fault zones containing lenses of sheared serpentinite and schistose metavolcanic rocks separate the western and central belts, and an angular unconformity occurs between the central and eastern belts (Clark and others, 1962).

Before presenting our tectonic model, we will summarize pertinent petrologic, stratigraphic, and structural data from each belt and discuss the nature of the major fault zones that affect them.

WESTERN BELT

The western belt is separated from the central belt to the east by a system of major faults whose southern segment is called the Melones fault zone (Clark, 1960) and whose northern segments are marked by major ultramafic masses (Fig. 1). The western belt actually consists of several discrete fault-bounded structural units. To simplify our discussion, we will divide the belt south of the American River into three tectonically significant units that we have informally named A, B, and C (Fig. 1). North of the American River, the Smartville block separates A and C. From the American to the Tuolumne River, A and C are separated by unit B, and south of the Tuolumne River, they are separated by the Bear Mountains fault zone. Both B and C contain appreciable thicknesses of submarine basaltic and andesitic pyroclastic rocks, lava, and interbedded volcaniclastic rocks (Clark, 1964; Morgan, 1973). B, locally sandwiched between the Bear Mountains

Geological Society of America Bulletin, v. 86, p. 1329–1336, 3 figs., October 1975, Doc. no. 51001.

fault zone and unit C, is a tectonic mélange (Duffield and Sharp, 1975). Its northern and southern extent are not known at present.

Clark (1964) discussed the stratigraphy of A and C separately, although earlier geologists felt that the same stratigraphic units occurred on both sides of the Bear Mountains fault zone. A, west of the Bear Mountains fault zone, consists of the Gopher Ridge volcanics, up to 4.3 km of basaltic, andesitic, and locally abundant rhyolitic pyroclastic rocks and lavas, which are overlain by and intertongue with the Salt Spring slate and Merced Falls slate. Late Oxfordian–early Kimmeridgian fossils occur in the Salt Spring slate, which contains graywacke, conglomerate, and minor limestone lenses in addition to slate. The thickness was not reported. This unit is considered to be the same age as the Mariposa Formation (discussed below), the youngest unit known east of the Bear Mountains fault zone. The Salt Spring slate is overlain by the Copper Hill volcanics, up to 2.1 km of mainly andesitic pyroclastic rocks that closely resemble the Gopher Ridge volcanics. According to Clark (1964), the Copper Hill volcanics are the youngest rocks in the western belt and may be Kimmeridgian or younger.

C, lying between the Bear Mountains and Melones fault zones, contains the following Mesozoic units: the Logtown Ridge Formation, with as much as 3 km of basaltic to andesitic volcanic breccia, pillow lava, tuff, and sandstone that are probably entirely of Callovian age along the Cosumnes River (Duffield and Sharp, 1975); the Peñon Blanco volcanics, with as much as 4.3 km of mafic tuff, volcanic breccia, and lava exposed along the Merced River; and the Mariposa Formation, which contains as much as 1.2 km of slate, tuff, and graywacke ranging from Oxfordian to Kimmeridgian age (Clark, 1964). By virtue of their position stratigraphically below the Mariposa Formation on the Merced River and their strikingly similar lithology, Clark (1964) believed that the Peñon Blanco volcanics are essentially the same age as the Logtown Ridge Formation, which underlies beds of the Mariposa Formation on the Cosumnes River (Duffield and Sharp, 1975). An additional formation, the Cosumnes, considered by Clark (1964) and Taliaferro (1942) to underlie the Logtown Ridge Formation along the Cosumnes River, the type locality of both units, has been remapped and split into two parts by Sharp and Duffield (1973; Duffield and Sharp, 1975). The upper part is now included in the Logtown Ridge and the lower is considered part of a mélange (unit B, discussed below). The result is that the Cosumnes Formation no longer exists at its type locality! Nonetheless, the name has been applied (for example, Eric and others, 1955) to other units to the south, in the Sonora quadrangle, that were considered to underlie the Logtown Ridge.

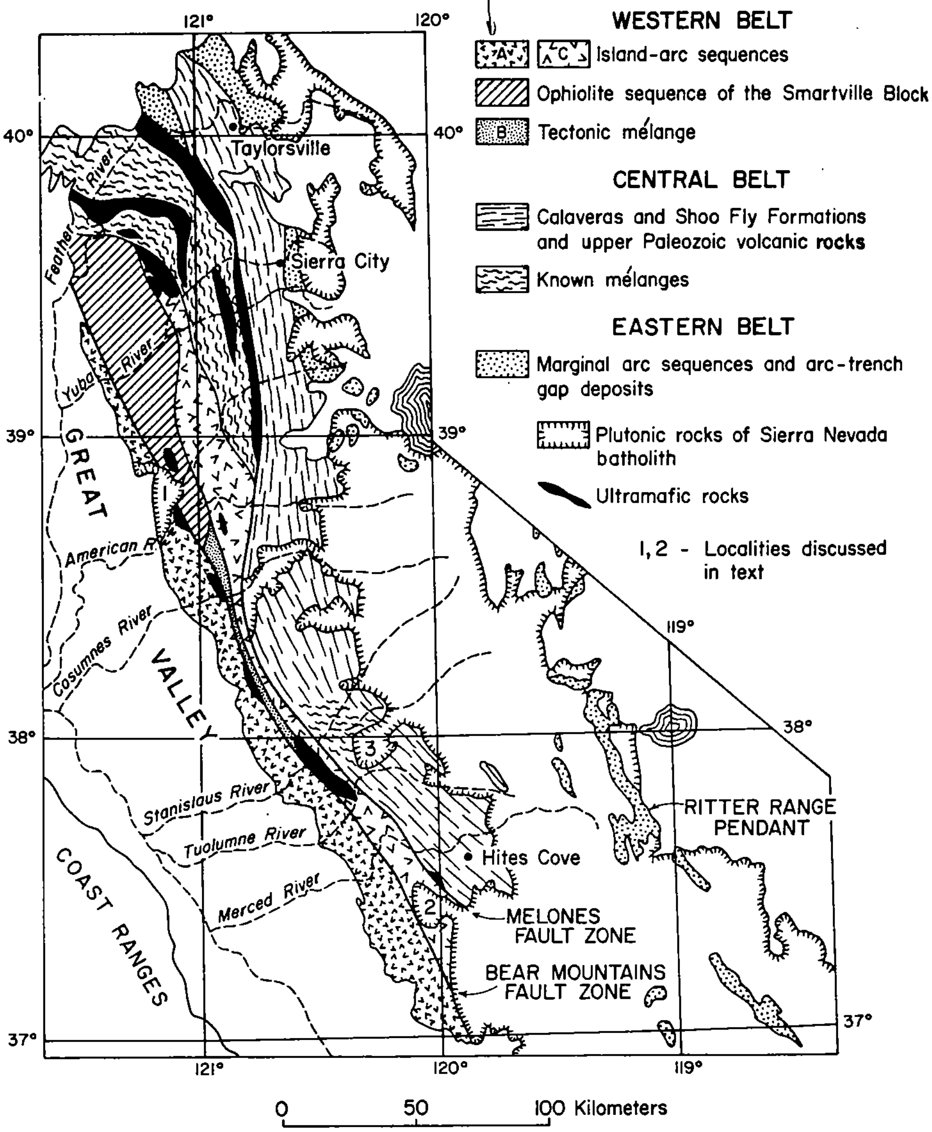

Figure 1. Generalized map showing the lithic belts of the Sierra Nevada in central California. Relations are shown diagrammatically. Mélanges are more extensive in the central belt than shown. Paleozoic rocks occur in many parts of the eastern belt but are not distinguished from Mesozoic rocks.

It is important to note that the actual base of the Logtown Ridge is unknown; instead, its lower parts are truncated by faults that juxtapose it with unit B (discussed below; Duffield and Sharp, 1975). The correlative Peñon Blanco volcanics, on the other hand, overlie an ultramafic complex on the Tuolumne River (Fig. 1) and may thus rest on oceanic crust and mantle (Morgan, 1973).

We interpret that stratigraphically and structurally complex sequence of basaltic to andesitic pyroclastic rocks, lava, and interbedded volcaniclastic sedimentary rocks in A and C as products of a Middle to Late Jurassic oceanic volcanic arc situated at a convergent plate boundary. The distinctive assemblage of rock types and linear geographic distribution are characteristic of modern arcs (Mitchell and Reading, 1969). Most of the Jurassic pyroclastic rocks were deposited in a marine environment, perhaps as submarine lahars from subaerial eruptions (Clark, 1964) or by sloughing of coarse material erupted and brecciated in submarine vents (Schweickert, unpub. data). Pillow lava also occurs locally. Except for their more mafic character, the pyroclastic rocks are similar to Miocene submarine ash-flow deposits in Japan described by Fiske and Matsuda (1964).

Closely correlative units occur in the western Jurassic belt of the Klamath Mountains (Irwin, 1960). The Galice and Rogue Formations, like their respective counterparts, the Mariposa and Logtown Ridge

Formations, probably represent a northwestern continuation of the oceanic volcanic arc into southwestern Oregon.

B, called the "western belt of the Calaveras Formation" by Clark (1964) and by earlier workers, is actually a tectonic mélange lying structurally beneath the Logtown Ridge Formation (Duffield and Sharp, 1975). According to Sharp and Duffield (1973), most of Clark's Cosumnes Formation is part of the mélange, but the fossiliferous, stratigraphically coherent part of the Cosumnes is assigned to the lower part of the stratigraphically intact Logtown Ridge and is named the Goat Hill Member. The mélange forms a narrow strip averaging 2.5 km wide that separates units A and C throughout its extent. It contains tectonic blocks of metasedimentary and metavolcanic rocks immersed in a pervasively sheared fine-grained matrix. Nearly all Paleozoic fossils in the western Sierra Nevada have come from limestone blocks in B. Although Clark (1964), Douglass (1967), and earlier workers used the fossils in B to date unfossiliferous rocks of the central belt east of the Melones fault zone, we feel that the tectonic contacts both of B and of the limestone blocks themselves preclude such a correlation. Several genera of Permian fusulinids from limestone in B have distinct asiatic or Tethyan affinities (Douglass, 1967), and several genera have not been identified elsewhere in the western United States. According to Douglass (1967), the Tethyan nature of the faunas indicate a lack of intermingling with other Permian forms indigenous to North America.

Numerous high-angle fault zones occur in the western belt. Cross sections of individual fault blocks, incorporating top determinations, relations between bedding and cleavage, and stratigraphic interpretations, suggest the presence of tight, locally isoclinal folds with axial surfaces that dip steeply east and parallel the regional schistosity (see Clark, 1960, Pl. 4; 1964, Pls. 2 through 8, 11; Eric and others, 1955, Pl. 2). Most published cross sections also suggest that C generally forms an east-dipping homocline with few folds, and A, west of the Bear Mountains fault zone, contains abundant isoclinal folds. However, previous structural interpretations in the region must be accepted with some reservation until the extent of chaotic units or mélange is better known. The nature of the contacts between epiclastic rocks, such as the Mariposa Formation, and intimately associated volcanic rocks is often obscure.

The deformation that produced tight folds and a penetrative, approximately axial-plane cleavage in A and C affects rocks as young as Kimmeridgian; the structures themselves are cut by plutons with minimum K-Ar dates of 125 to 136 m.y. (1 and 2, Fig. 1). The age of the shearing that produced the mélange in B is post-Permian; a minimum age is not yet established. Duffield and Sharp (1975) suggest that the intermixing of the mélange either predated the Logtown Ridge Formation and hence is pre-Callovian or, more likely, predated the juxtaposition of the Logtown Ridge Formation with the mélange. Significantly, no tectonic fragments of distinctive Logtown Ridge augite porphyry were reported in the mélange.

Smartville Block

A third major sequence in the western belt, not formerly recognized, extends north from the American River to the south fork of the Feather River and lies between the northern extensions of A and C (Fig. 1). Named the Smartville block by Cady (1975) after a town on the Yuba River, the block averages 11 km across, is bounded by the Bear Mountains fault zone on the west and an unnamed fault zone on the east, and is flanked on both sides by belts of andesitic and basaltic rocks described above. Although previous workers did not distinguish this block from flanking blocks, our mapping has revealed significant lithologic and structural differences. Most volcanic rocks are pillow basalt, although subvertical swarms of basaltic dikes are common. The block is evidently an antiform with gently dipping limbs, and in its core are pods and lenses of metagabbro and metatrondhjemite. All of these rocks were deformed and metamorphosed prior to the intrusion of several large ovoid granodioritic plutons, some with trondhjemitic cores, that have produced thick contact aureoles with mineral assemblages of hornblende-hornfels facies in the metabasalt (Compton, 1955). None of the granodioritic bodies within the Smartville block has been dated, but similar bodies to the north and south have yielded 131- to 146-m.y. K-Ar hornblende ages (Evernden and Kistler, 1970). Volcanic rocks of the Smartville block are markedly schistose near the boundary fault zones but appear relatively undeformed in the interior of the block.

On-land assemblages of pillow basalt, "sheeted" or diked mafic complexes, and gabbroic rocks are now commonly interpreted as fragments of oceanic crust and, if ultramafic rocks are present, upper mantle (Coleman, 1971). We believe the Smartville "ophiolite" is a fragment of Jurassic oceanic lithosphere, even though evidence for its age is circumstantial. Its close proximity to rocks formed in a Middle to Late Jurassic volcanic arc and the apparent lack of abundant chert suggest that the oceanic crust formed in an interarc or marginal basin (Karig, 1971). To speculate further, perhaps the northern extension of either A or C is a remnant arc (Karig, 1971, 1972) that may have earlier split away during formation of the interarc basin. Data from the Smartville block and its environs are too meager to preclude such possibilities, but the distinctive lithology of the block seems well established.

Geophysical Data

Cady (1975) has studied magnetic and gravity anomalies in the Great Valley and western Sierra Nevada to deduce three-dimensional properties of the blocks in the western belt and to infer the nature of the "Sierran" basement beneath the Great Valley. His work, together with published well data, suggests that mafic volcanic rocks, with some serpentinite and gabbro, form the bulk of the basement and that gabbro or related mafic intrusive rock causes the Great Valley gravity and magnetic anomalies. Thus, Great Valley basement more nearly resembles oceanic crust rather than the volcanic arc deposits of the western belt in composition, even though geophysical modeling yields an unreasonable, but as yet unexplained, thickness of 30 km for the layer in question. Ophiolite beneath Tithonian sedimentary rocks of the Great Valley sequence in the Coast Ranges (Bailey and others, 1970) can be projected beneath the Great Valley and, indeed, is compositionally similar to the basement Cady (1975) postulated there. The ophiolite yields dates of approximately 151 to 161 m.y. (Lanphere, 1971; Hopson and others, 1973).

CENTRAL BELT

Our reconnaissance of the central belt, believed to be largely or entirely of Paleozoic age, has revealed that it includes both conventionally deformed, stratigraphically coherent terranes and extensive chaotic terranes.

South of the south fork of the American River, the central belt is separated from the western belt by the Melones fault zone. The name Calaveras Formation is now broadly applied to all rocks in the southern half of the central belt, following Turner's (1893a) use of the name for "all rocks of Paleozoic age in the Sierra Nevada." The age of these rocks has been generally assumed to be Permian-Carboniferous on the basis of (1) one fossil locality at the south end of the belt near Hites Cover (Turner, 1893a; Fig. 1), from which the collections have evidently been lost (Clark, 1964); and (2) more abundant fossils from limestone blocks in the "western belt of Calaveras" (B in this paper; Clark, 1964), now known to be tectonic mélange (Sharp and Duffield, 1973). Distinctive stratigraphic markers are apparently not present in the central belt.

The internal structure of this enormous terrane is essentially unknown, but it is commonly assumed that rocks are arranged in a steeply east-dipping homocline (Bateman and Eaton, 1967). According to Clark (1964), the belt is mainly a monotonous sequence of black carbonaceous slate and siltstone interbedded with abundant chert and with several large lenticular masses of limestone north and southeast of Sonora. In addition, Clark believes the lower part of the formation includes a volcanic member of schistose pyroclastic rocks. No estimate of thickness is reported by Clark, but if the formation were indeed a steeply east-dipping homocline, its thickness would be colossal, because the belt is as much as 40 km wide.

However, studies in progress along the Stanislaus River suggest that the structure is much more complex, at least in some areas. Along the river from Camp Nine Powerhouse to the confluence of the South Fork, and especially along Rose Creek, are extensive exposures of mélange consisting mainly of fragments of chert of all sizes and shapes in a matrix of dark mudstone and argillite that in some localities is pervasively sheared. Some large blocks of thinly bedded chert show tight chevron folds. Most chert fragments are elongate and define a lineation that plunges steeply in the plane of foliation. Locally, shearing is so intense that the rocks appear to be mylonitic. Nowhere in this area are original stratigraphic relationships or bedding preserved, except within isolated blocks of chert. The extent of the mélange and the nature of its contacts with coherent rocks are not known, but work in progress (Schweickert and Wright, 1975) has revealed that similar rocks and structures extend south of the South Fork Tuolumne River.

Baird (1962) also studied an area along the Stanislaus River and concluded that pronounced planar structures in the large mass of marble near Columbia do not represent bedding but instead are secondary foliations that record a pronounced penetrative deformation. Significantly, no recognizable fossils have been recovered from the large lenticular masses of marble in the central belt; in general they are more highly deformed and recrystallized than the tectonic blocks of limestone in B west of the Melones fault zone.

North of the South Fork American River, between lat 39° and 40°N, the central belt comprises two terranes that contrast significantly in deformational style and are separated by a major fault zone that Clark (1960) considered the northern continuation of the Melones but that E. M. Moores (personal commun., 1974) considers an older feature. For convenience, we will use the name "Melones" fault zone for this structure. The name Shoo Fly Formation has recently been applied to weakly metamorphosed epiclastic rocks east of the Melones zone, based on lithologic similarity with the fossiliferous Taylorsville Formation; these rocks thus may be of Silurian or older age (Clark and others, 1962).

Along the North Fork Yuba River, the metasedimentary rocks are mainly phyllite with minor chert, siltstone, and quartzose sandstone, and they evidently form a northwest-trending homoclinal sequence with steep northeast dips. Where bedding can be recognized, it is generally parallel to well-developed slaty and phyllitic cleavage, except near hinges of tight minor folds. A major upper Paleozoic shear zone truncates the sequence near Sierra City (Schweickert, 1974) and probably extends to the northern end of the Sierra Nevada (E. M. Moores, personal commun., 1974), but its significance is as yet unclear. Along their eastern margin, the metasedimentary rocks are unconformably overlain by a thick metavolcanic sequence that is rich in dacitic rocks at its base and largely andesitic in its upper parts. Upper Devonian fossils have been recovered from near the top of the dacitic base (Anderson and others, 1974), and the andesitic rocks contain strata as young as Mississippian (Diller, 1908). This volcanic accumulation, which may exceed 6 km in thickness, closely resembles other arc-generated volcanic complexes; it has been related to plate consumption at the margin of North America during Devonian time (Hamilton, 1969, p. 2418; Moores, 1970; Burchfiel and Davis, 1972; Silberling, 1973).

West of the Melones fault zone at this latitude, a terrane with areally extensive tectonic mélange separates the deformed, but stratigraphically coherent, part of the central belt from the western belt. The chaotic nature of much of this terrane is clearly illustrated by the excellent maps of Hietanen (1973). Much of the mélange is made up of sheared basaltic volcanic rocks with numerous tectonic slices of serpentinite, rhyolite, and chert. It probably represents dismembered ophiolite. Tectonic blocks of amphibolite gneiss occur locally, as on the North Fork Feather River. Again, the age, or ages, of the deformation recorded in the mélange cannot be closely specified. Probable Permian and Carboniferous fossils occur locally in limestone blocks in the terrane. In its northern part, it is intruded by several large, zoned plutons, four with K-Ar hornblende ages ranging from 131 to 146 m.y. (Evernden and Kistler, 1970). It can only be concluded that at least part of the shearing is post-Permian and pre–Late Jurassic.

Davis (1969) correlated the western part of the central belt with the vast "western Paleozoic and Triassic belt" of Irwin (1960) in the Klamath Mountains. Scattered limestone blocks in the Klamath terrane contain Permian and Triassic fossils. Our limited reconnaissance of this belt, together with the works of Davis (personal commun., 1973), Cashman (1974, and personal commun., 1974), and Cox and Pratt (1973), suggests that mélanges may be widespread there, supporting Davis' (1969) original correlation.

In detail, the central belt of the Sierra Nevada may be fully as complex as the Franciscan of the California Coast Ranges, but additional field work is clearly needed before it can be adequately interpreted. The Calaveras–Shoo Fly terranes may in part record miogeoclinal sedimentation followed, in the northern Sierra, by later volcanic arc activity at a Paleozoic plate edge. Certain tectonic mélanges in the central belt may be subduction zone assemblages, structurally analogous to the Franciscan Complex. Some chaotic terranes may have resulted, at least in part, from plate-consumption events during Mesozoic time, but no direct evidence of timing has yet been recognized.

EASTERN BELT

Mesozoic rocks of the eastern belt unconformably overlie the Paleozoic rocks of the central belt along the North Fork American River (Clark and others, 1962), but this relationship can be observed in very few other places. South of the American River, plutonic rocks of the Sierra Nevada batholith have obliterated the unconformity, and Mesozoic rocks of the eastern belt now occur, together with Paleozoic rocks, chiefly as pendants within the batholith (Fig. 1); this same unconformity may be exposed in certain pendants (Brook and others, 1974). Sparse fossils indicate that Mesozoic volcanic and sedimentary rocks of the belt are mainly of Late Triassic to Early Jurassic age. Slightly younger Middle and Upper Jurassic rocks occur at the north end of the belt near Taylorsville (Fig. 1). The most common Mesozoic rocks in the eastern belt are silicic pyroclastic rocks and ignimbrite, interbedded with andesitic lava, and marine and nonmarine volcanic sandstone and mudstone. Upper Triassic rocks are generally limestone and sandstone. As much as 8.6 km of such volcanic and volcaniclastic rocks occur in the Ritter Range pendant (Rinehart and others, 1959). Mesozoic rocks of the eastern belt will be discussed more fully elsewhere (R. A. Schweickert, in prep.). We interpret the Mesozoic rocks of the belt, together with Upper Triassic and Lower Jurassic plutonic rocks of the eastern Sierra Nevada and the White-Inyo Mountains (Evernden and Kistler, 1970; R. A. Schweikert, in prep.), as remnants of a west-facing Andean-type marginal arc that developed in

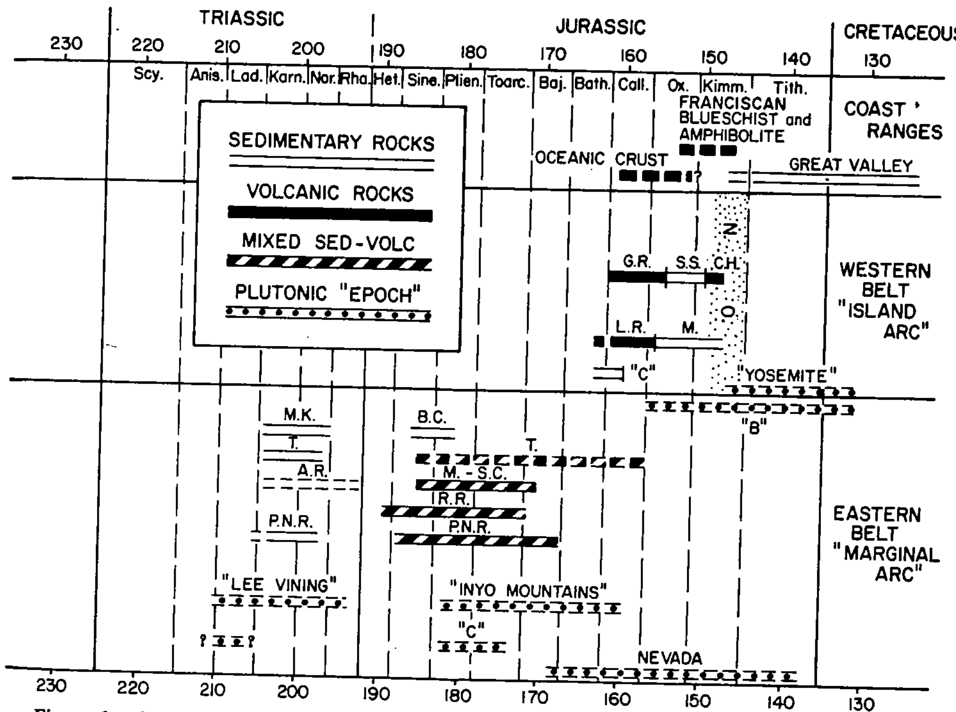

Figure 2. Summary diagram of known age relationships of middle Mesozoic rocks of the Sierra Nevada and adjacent regions. Boundaries of faunal stages of the Triassic and Jurassic Systems were assigned absolute ages according to Harland and others (1964); faunally dated formations were assigned approximate age ranges accordingly. The base of the Tithonian stage of the Upper Jurassic Series is a compromise between the figures of Suppe (1969; 150 m.y.) and Coleman and Lanphere (1971; 140 m.y.). Coast Ranges: Sources: Coleman and Lanphere (1971), Hopson and others (1975), Jones (1975), Lanphere (1971). Western belt: G.R. = Gopher Ridge volcanics; S.S. = Salt Spring slate; C.H. = Copper Hill volcanics; L.R. = Logtown Ridge Formation; M. = Mariposa Formation; "C" = Cosumnes Formation; N.O. and stippled pattern = approximate span of "Nevadan orogeny." Sources: Clark (1964), Duffield and Sharp, (1975). Eastern belt: M.K. = Mineral King pendant; B.C. = Boyden Cave pendant; T. = Taylorsville area; A.R. = American River; M.-S.C. = Milton-Sailor Canyon Formations; R.R. = Ritter Range pendant; P.N.R. = Pine Nut Range. Sources: Christensen (1963), Crickmay (1933), Clark and others (1962), Imlay (1961), Jones and Moore (1973), McMath (1966), Noble, (1962, and personal commun., 1969), and Rinehart and others (1959). Plutonic epochs: "Lee Vining," "Inyo Mountains," and "Yosemite" of Evernden and Kistler (1970), "B," "C," ?··? of Lanphere and Reed (1973), Nevada of Silberman and McKee (1971), and Smith and others (1971).

Late Triassic time along the complex truncated Paleozoic continental margin of North America (see Burchfiel and Davis, 1972). Nonvolcanic pendants in the central and southern Sierra near lat 37°N., which contain Jurassic and Triassic rocks (Fig. 1; Jones and Moore, 1973), might be viewed as part of an arc-trench gap sequence associated with the arc. Certain tectonic mélanges in the central belt might record the subduction responsible for magmatic arc activity, although mélanges of various ages are probably represented.

MAJOR FAULT ZONES

Clark (1960) used the name "Foothills fault system" for the major fault zones in the western Sierra Nevada and recognized the Melones and Bear Mountains fault zones as the most important parts of the system south of the Cosumnes River. North of the Cosumnes, the fault system encompasses several additional branching fault zones, some of which have been named by Hietanen (1973).[1] In general, the faults consist of vertically to steeply east-dipping zones of sheared rock up to about 6 km wide, with rather linear mapped traces. Many faults are delineated either wholly or in part by lenses of sheared serpentinite or by lenses of schistose metavolcanic rocks. In fact, faults have often been mapped solely on the presence of sheared serpentinite or schist, in the absence of other stratigraphic evidence. Undoubtedly, many faults, lacking such distinctive markers, have not been detected. Tectonic blocks of recrystallized limestone, occasionally fossiliferous, commonly occur within fault zones.

Unlike conventional high-angle normal, reverse, and strike-slip faults and low-angle thrusts, Sierran faults do not systematically repeat or offset dated stratigraphic successions. Consequently, direct conclusive evidence for the nature and amount of offset along the Sierran fault zones has not been recognized, even though displacements have been *interpreted* as high-angle reverse (Knopf, 1929; Ferguson and Gannett, 1932), strike slip (Clark, 1960, 1964), thrust (Taliaferro, 1942; Davis, 1969), and a combination of strike slip preceded by thrust (Cebull, 1972). The fault zones disrupt rocks as young as Oxfordian-Kimmeridgian (157 to 145 m.y.); locally they are truncated by plutons that have yielded K-Ar dates of 125 to 136 m.y. (Evernden and Kistler, 1970; localities 1 and 2, Fig. 1). These data bracket the latest movements along some faults as Late Jurassic but do not preclude earlier offsets. Faults of several ages probably comprise the "Foothills fault system"; some may have originated appreciably earlier than Late Jurassic time. Displacement histories are undoubtedly complex. We prefer not to attach generic or geometric labels to the faults at this time; instead, we emphasize that they fundamentally record the juxtaposition of structural units with diverse tectonic histories. In a sense, the Sierran faults most closely resemble moderately to steeply dipping faults in the Franciscan Complex that similarly juxtapose rock units bearing no apparent deformational, metamorphic, or stratigraphic relation to one another (Cowan, 1974). The former, however, are larger scale features and probably have much greater displacements.

TECTONIC MODEL

On the basis of the lithologic and structural data summarized above, we believe that (1) the western belt includes a Jurassic volcanic arc and related oceanic lithosphere; and (2) the central belt is a complex Paleozoic continental margin upon which an Andean-type marginal arc, now represented in the eastern belt, was constructed in Late Triassic to Late Jurassic time. These partly coeval rock assemblages, formed in different petrotectonic settings, were juxtaposed during the Late Jurassic collision of the volcanic arc with the North American continental margin. Late Triassic to Late Jurassic plate interaction and consumption in the western Sierra Nevada are recorded by major fault zones and, more broadly, by the penetrative shear-fracture fabric of tectonic mélanges.

Figure 2 summarizes the age data known to us regarding the pre-Tithonian geology of the Sierra Nevada. Most absolute ages can only be considered approximations. In particular, there is considerable debate over the age of the base of the Tithonian Stage of the Upper Jurassic Series, and the 145-m.y.

[1] For convenience, we have adopted the name "Melones" for the easternmost of these fault zones, as did Lydon and others (1960), Burnett and Jennings (1962), and Hietanen (1973). Nonetheless, there is a possibility that fault segments of different ages are involved. Extensive revision of existing nomenclature of both faults and Paleozoic units in the Sierra Nevada is clearly necessary.

date chosen in Figure 2 is merely a compromise. In addition, the number of distinct magmatic "epochs" in the Sierra Nevada is controversial. We have included three events postulated by Evernden and Kistler (1970) and other, in part different, epochs that Lanphere and Reed (1973) based on concordant K-Ar dates.

Figure 3 illustrates our preferred model for the pre–Late Jurassic tectonic evolution of the Sierra Nevada:

1. During Late Triassic time, a marginal arc and subduction zone were initiated along the western edge of the North American plate, consuming oceanic lithosphere to the west. Plate consumption, as recorded by the eastern belt and associated plutonic rocks, ceased in Middle or Late Jurassic time.

Faunal evidence in all but the northernmost part of the belt suggests that volcanism ceased prior to Late Jurassic time. If rocks near Taylorsville are included, however, the marginal arc may have been active during early Late Jurassic time and may thus have been partly contemporaneous with the island arc of the western belt. Also, radiometric ages of plutonic rocks in the eastern Sierra Nevada and the White-Inyo Mountains (Evernden and Kistler, 1970) suggest that magmatic activity in that region ceased during Middle Jurassic time. However, Middle and Upper Jurassic plutonic rocks of northwestern and north-central Nevada (Smith and others, 1971; Silberman and McKee, 1971) could be considered part of the magmatic arc and thus would reflect a northeast landward shift in magmatic activity from Late Triassic through Middle and Late Jurassic time.

We suggested above that at least part of the areally extensive tectonic mélanges in the central belt formed during this Late Triassic to Middle or Late Jurassic plate consumption. The central belt may contain mélanges of many ages; in a real sense, age of a mélange is difficult to specify. In general, fossils from tectonic inclusions merely date rocks that were affected by the deformation that produced a given mélange. The age of the deformation itself may overlap or, perhaps more likely, postdate the ages of inclusions. Mélanges in the western Sierra Nevada contain limestone blocks that have yielded fossils ranging from Devonian (L. Clark, personal commun., 1973) to Permian in age. Further collections might yield fossils of still other ages in Sierran mélanges. North of lat 39°N, the mélanges are cut by plutons that have been dated (K-Ar, hornblende) at 131 to 146 m.y., providing a younger limit on age of deformation. Although no firm conclusions about the precise age of the deformation of the mélanges can yet be reached, we feel that available geologic evidence is compatible with our suggestion.

2. Near the end of Middle Jurassic time, a separate east-facing island arc developed some distance from the marginal continental system described above. Although the arc, now represented by the western belt, consists predominantly of volcanic and volcaniclastic rocks, it apparently contained some fragments of Paleozoic rocks with Tethyan faunas. Fragmentation of the arc and formation of an interarc basin floored by the oceanic lithosphere of the Smartville block probably occurred during Late Jurassic time. Volcanism and concurrent sedimentation ceased in Kimmeridgian time.

Again, we feel it is necessary to postulate this separate and, in particular, *east-facing* arc for several reasons. Although magmatism in both the western and eastern belts was in part coeval (Fig. 2), the arcs clearly are not coincident (Fig. 3) but instead are separated by tectonic mélanges and (or) major fault zones. Most importantly, new oceanic crust generated to the west (behind) such an eastward-migrating volcanic arc might well have formed the ophiolitic floor for the basal Tithonian beds of the Great Valley sequence in the Coast Ranges. Middle to Upper Kimmeridgian fossils occur in one locality (Jones, 1975). The Great Valley ophiolite is pre-Tithonian in age (Lanphere, 1971; Hopson and

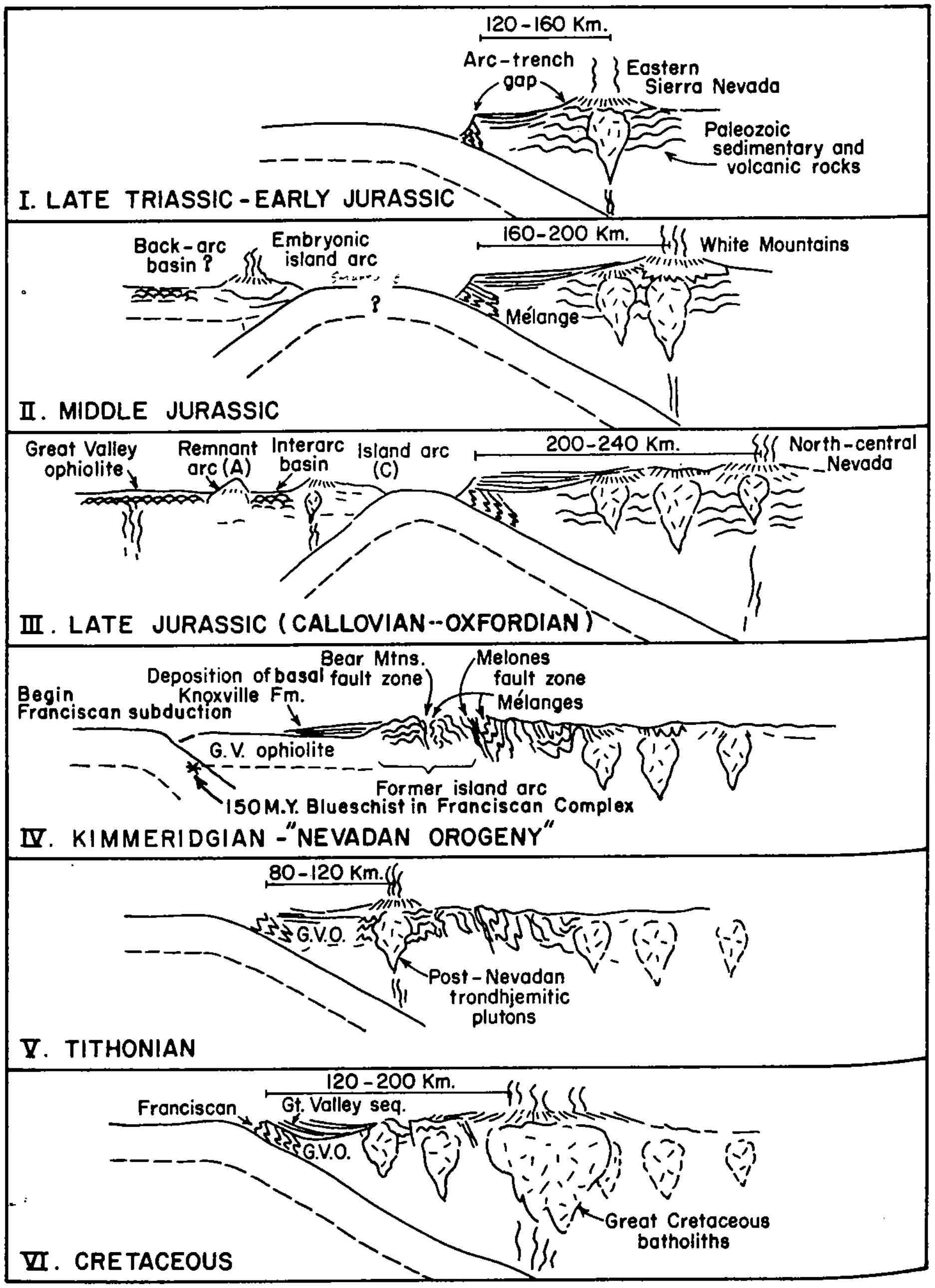

Figure 3. Hypothetical schematic sections showing postulated tectonic evolution of the Sierra Nevada during Mesozoic time.

others, 1975) and is clearly coeval with most of the volcanic and volcaniclastic rocks in the western belt (Fig. 2).

3. The continental marginal arc (eastern belt) and the oceanic arc (western belt) approached one another by consuming intervening lithosphere. Approximately 150 m.y. ago, the two opposing arc-trench systems collided, extinguishing magmatic activity in both arcs (Fig. 2). The collision also was probably responsible for (1) closure of the southern part of the interarc basin in the western arc system, leaving only the remnant Smartville block to the north; and (2) the regional deformation affecting rocks as young as Kimmeridgian that is generally termed the "Nevadan orogeny" (sensu strictu). Nevadan structures, including major fault zones, are cut by plutons of Tithonian and younger ages.

4. At approximately the same time as the arc-continent collision, subduction stepped west, oceanward of the accreted island arc, initiating the Sierran-Franciscan arc-trench system. The latter remained active through Mesozoic time. Upper Jurassic plutons of the western Sierra Nevada (Evernden and Kistler, 1970) thus are the initial magmatic products of the "new" Sierran arc and, fittingly, are low-potash diorite, tonalite, granodiorite, and trondhjemite.

This model successfully explains several seemingly unrelated geologic features: (1) the juxtaposition of island-arc rocks with a continental margin that already possessed a marginal arc; (2) the pre-Tithonian Great Valley ophiolite, which assumed a back-arc or marginal basin setting relative to the Sierra foothills arc and received a vast supply of arc-derived volcaniclastic sediment (the Great Valley sequence); and (3) limestone blocks with "Tethyan" faunas, accounted for as fragments of an older arc complex that were rafted along with the easterly migrating island arc.

The data used to support our preferred model may also bear on the inception of the Franciscan subduction regime. In particular, the 150-m.y. metamorphic ages determined on high-grade blueschist that occurs as tectonic blocks and sheets in the Franciscan Complex in the Coast Ranges (Coleman and Lanphere, 1971; Suppe and Armstrong, 1972) may coincide with, or at least approximate, the postulated collision event in the Sierra foothills (Fig. 2). Also, the metamorphic event seems to postdate the generation of oceanic crust that lies at the base of the Great Valley sequence. Most of the high-grade blueschist, eclogite, and amphibolite blocks in the Franciscan are apparently recrystallized mafic igneous rocks. We suggest that they are fragments of the pre-Tithonian oceanic crust and upper mantle that later formed the basement for the Great Valley sequence. As such, they record the initiation of the Franciscan regime about 150 m.y. ago, when pre-Tithonian ophiolite was first subducted and subjected to high-pressure metamorphism (Fig. 3).

We hasten to add, however, that there are several shortcomings to the model that should not be overlooked. The apparent close timing of Nevadan events in the Sierras and Coast Ranges may in part be due to the uncertainties in the absolute time scale discussed above. Also, at least one pluton[2] in the central belt of the western Sierra (loc. 3, Fig. 1) has yielded older (144 to 162 m.y.) discordant K-Ar ages (Evernden and Kistler, 1970), in apparent conflict with our suggestion that the Jurassic Sierra Nevada batholith had its inception after the 150-m.y. B.P. collision event. Indeed, this pluton occupies a tectonic position similar to that of the Ironside Mountain batholith and Forks of Salmon pluton of the western Klamath Mountains, both of which have ages of more than 150 m.y. (Lanphere and others, 1968). The radiometric ages of these plutons suggest they are part of the Upper Triassic–Middle Jurassic Andean-type arc ("eastern belt" of Figs. 1, 2, 3) that developed along the continental margin, but their spatial location immediately adjacent to the inferred collision or suture zones in the western Sierra and western Klamath Mountains is difficult to reconcile with such an interpretation. We have thus been unable to relate these plutons to any plausible tectonic model, assuming their published K-Ar ages are meaningful; their true ages might be considerably older. The plutons remain a petrologic and tectonic enigma.

Notwithstanding these limitations, we believe our preferred model has merit. We present it as a working hypothesis and hope that it will kindle other geologists' interest in this vast, complex region.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the following individuals, who shared their time and thoughts in informal discussions and on field trips: W. R. Dickinson, E. M. Moores, B. Morgan, and especially J. W. Cady, L. D. Clark, W. A. Duffield, and R. V. Sharp, who also allowed access to data prior to publication. G. A. Davis, W. R. Dickinson, and B. M. Page read and criticized an earlier manuscript; B. C. Burchfiel and E. M. Moores reviewed and criticized the final version. To each of these individuals we are grateful; however, we alone accept responsibility for any errors of fact or interpretation.

[2] Work in progress (Schweickert and Wright, 1975) has shown that this pluton postdates the deformation of chaotic rocks in the Calaveras Formation; the K-Ar ages of this pluton and structural data indicate that the chaotic deformation of the Calaveras significantly predates the collision event postulated in this paper.

REFERENCES CITED

Anderson, T. B., Woodard, G. D., Strathouse, S. M., and Twichell, M. K., 1974, Geology of a Late Devonian fossil locality in the Sierra Buttes Formation, Dugan Pond, Sierra City quadrangle, California: Geol. Soc. America Abs. with Programs, v. 6, p. 139.

Bailey, E. H., Blake, M. C., Jr., and Jones, D. L., 1970, Onland Mesozoic oceanic crust in California Coast Ranges: U.S. Geol. Survey Prof. Paper 700–C, p. C70–C81.

Baird, A. K., 1962, Superposed deformation in the central Sierra Nevada foothills east of the Mother Lode: California Univ. Dept. Geol. Sci. Bull., v. 42, p. 1–70.

Bateman, P. C., and Eaton, J. P., 1967, Sierra Nevada batholith: Science, v. 158, p. 1407–1417.

Brook, C. A., Nokleberg, W. J., and Kistler, R. W., 1974, Nature of angular unconformity between the Paleozoic metasedimentary rocks and the Mesozoic metavolcanic rocks in the eastern Sierra Nevada, California: Geol. Soc. America Bull., v. 85, p. 571–576.

Burchfiel, B. C., and Davis, G. A., 1972, Structural framework and evolution of the southern part of the Cordilleran orogen, western United States: Am. Jour. Sci., v. 272, p. 97–118.

Burnett, J. L., and Jennings, C. W., 1962, Geologic map of California, Chico sheet: California Div. Mines and Geology Map Sheet, scale 1:250,000.

Cady, J. W., 1975, Magnetic and gravity anomalies in the California Great Valley and western Sierra Nevada metamorphic belt: Geol. Soc. America Spec. Paper 168 (in press).

Cashman, P. H., 1974, Mélange terrane in the western Paleozoic and Triassic subprovince, Klamath Mountains, California: Geol. Soc. America Abs. with Programs, v. 6, p. 153.

Cebull, S. E., 1972, Sense of displacement along Foothills fault system: New evidence from the Melones fault zone, western Sierra Nevada, California: Geol. Soc. America Bull., v. 83, p. 1185–1190.

Christensen, M. L., 1963, Structures of metamorphic rocks at Mineral King, California: Calif. Univ. Pubs. Geol. Sci., v. 42, p. 159–198.

Clark, L. D., 1960, Foothills fault system, western Sierra Nevada, California: Geol. Soc. America Bull., v. 71, p. 483–496.

——1964, Stratigraphy and structure of part of the western Sierra Nevada metamorphic belt, California: U.S. Geol. Survey Prof. Paper 410, 70 p.

Clark, L. D., Imlay, R. W., McMath, V. E., and Silberling, N. J., 1962, Angular unconformity between Mesozoic and Paleozoic rocks in the northern Sierra Nevada, California: U.S. Geol. Survey Prof. Paper 450B, p. B15–B19.

Coleman, R. G., 1971, Plate tectonic emplacement of upper mantle peridotites along continental edges: Jour. Geophys. Research, v. 76, p. 1212–1222.

Coleman, R. G., and Lanphere, M. A., 1971, Distribution and age of high-grade blueschists, associated eclogites, and amphibolites from Oregon and California: Geol. Soc. America Bull., v. 82, p. 2397–2412.

Compton, R. R., 1955, Trondhjemite batholith near Bidwell Bar, California: Geol. Soc. America Bull., v. 66, p. 9–44.

Cowan, D. S., 1974, Deformation and metamorphism of the Franciscan subduction zone complex northwest of Pacheco Pass, California: Geol. Soc. America Bull., v. 85, p. 1623–1634.

Cox, D. P., and Pratt, W. P., 1973, Submarine chert-argillite slide-breccia of Paleozoic age in the southern Klamath Mountains, California: Geol. Soc. America Bull., v. 84, p. 1423–1438.

Crickmay, C. H., 1933, Mount Jura investigation: Geol. Soc. America Bull., v. 44, p. 895–926.

Davis, G. A., 1969, Tectonic correlations, Klamath Mountains and western Sierra Nevada, California: Geol. Soc. America Bull., v. 80, p. 1095–1108.

Diller, J. S., 1908, Geology of the Taylorsville region, California: U.S. Geol. Survey Bull. 353, 128 p.

Douglass, R. C., 1967, Permian Tethyan fusulinids from California: U.S. Geol. Survey Prof. Paper 593A, p. A1–A13.

Duffield, W. A., and Sharp, R. V., 1975, Geology of the Sierran foothills melange and adjacent areas, Amador County, California: U.S. Geol. Survey Prof. Paper 827 (in press).

Eric, J. H., Stromquist, A. A., and Swinney, C. M., 1955, Geology and mineral deposits of Angels Camp and Sonora quadrangles, Calaveras and Tuolumne Counties, California: California Div. Mines and Geology Spec. Rept. 41, 55 p.

Evernden, J. F., and Kistler, R. W., 1970, Chronology of emplacement of Mesozoic batholith complexes in California and western Nevada: U.S. Geol. Survey Prof. Paper 623, 43 p.

Ferguson, H. G., and Gannett, R. W., 1932, Gold quartz veins of the Alleghany district, California: U.S. Geol. Survey Prof. Paper 172.

Fiske, R. S., and Matsuda, T., 1964, Submarine equivalents of ash flows in the Tokiwa Formation, Japan: Am. Jour. Sci., v. 262, p. 76–106.

Hamilton, W., 1969, Mesozoic California and underflow of Pacific mantle: Geol. Soc. America Bull., v. 80, p. 2409–2430.

Harland, W. B., Smith, A. G., and Wilcock, B., eds., 1964, The Phanerozoic time scale: Geol. Soc. London Quart. Jour., v. 120A, 458 p.

Hietanen, A., 1973, Geology of the Pulga and Bucks Lake quadrangles, Butte and Plumas Counties, California: U.S. Geol. Survey Prof. Paper 731, 65 p.

Hopson, C. A., Frano, C. J., Pessagno, E., and Mattinson, J. M., 1973, Late Jurassic ophiolite at Point Sal, Santa Barbara County, California: Geol. Soc. America Abs. with Programs, v. 5, p. 58.

Hopson, C. A., Mattinson, J. M., and Pessagno, E., 1975, Record of Late Jurassic sea-floor spreading, California Coast Ranges: Geol. Soc. America Abs. with Programs, v. 7, p. 326.

Imlay, R. W., 1961, Late Jurassic ammonites from the western Sierra Nevada, California: U.S. Geol. Survey Prof. Paper 374–D, p. D1–D30.

Irwin, W. P., 1960, Geologic reconnaissance of the northern Coast Ranges and Klamath Mountains, California, with a summary of the mineral resources: California Div. Mines and Geology Bull. 179, 80 p.

Jones, D. L., 1975, Discovery of *Buchia rugosa* of Kimmeridgian age from the base of the Great Valley sequence: Geol. Soc. America Abs. with Programs, v. 7, p. 330.

Jones, D. L., and Moore, J. G., 1973, Lower Jurassic ammonite from the south-central Sierra Nevada, California: U.S. Geol. Survey Jour. Reserach, v. 1, p. 453–458.

Karig, D. E., 1971, Origin and development of marginal basins in the western Pacific: Jour. Geophys. Research, v. 76, p. 2542–2561.

——1972, Remnant arcs: Geol. Soc. America Bull., v. 83, p. 1057–1068.

Knopf, Adolph, 1929, The Mother Lode system of California: U.S. Geol. Survey Prof. Paper 157, 88 p.

Lanphere, M. A., 1971, Age of the Mesozoic oceanic crust of the California Coast Ranges: Geol. Soc. America Bull., v. 82, p. 3209–3212.

Lanphere, M. A., and Reed, B. L., 1973, Timing of Mesozoic and Cenozoic plutonic events in circum-Pacific North America: Geol. Soc. America Bull., v. 84, p. 3773–3782.

Lanphere, M. A., Irwin, W. P., and Hotz, P. E., 1968, Isotopic age of the Nevadan orogeny and older plutonic and metamorphic events in the Klamath Mountains, California: Geol. Soc. America Bull., v. 79, p. 1027–1052.

Lindgren, W., 1894, Sacramento, Calif.: U.S. Geol. Survey Geol. Atlas, folio 5, 3 p.

——1900, Colfax, California: U.S. Geol. Survey Geol. Atlas, folio 66, 10 p.

Lindgren, W., and Turner, H. W., 1894, Placerville, Calif.: U.S. Geol. Survey Geol. Atlas, folio 3, 3 p.

——1895, Smartsville, Calif.: U.S. Geol. Survey Geol. Atlas, folio 18.

Lydon, P. A., Gay, T. E., Jr., and Jennings, C. W., 1960, Geologic map of California, Westwood sheet: California Div. Mines and Geology Map Sheet, scale 1:250,000.

McMath, V. E., 1966, Geology of the Taylorsville area, northern Sierra Nevada: California Div. Mines and Geology Bull. 190, p. 173–183.

Mitchell, A.H.G., and Reading, H. G., 1969, Continental margins, geosynclines, and ocean floor spreading: Jour. Geology, v. 77, p. 629–646.

Moores, E. M., 1970, Ultramafics and orogeny, with models of the U.S. cordillera and the Tethys: Nature, v. 228, p. 837–842.

——1972, Model for Jurassic island arc–continental margin collision in California: Geol. Soc. America Abs. with Programs, v. 4, p. 202.

Morgan, B. A., 1973, Tuolumne River ophiolite, western Sierra Nevada, California: Geol. Soc. America Abs. with Programs, v. 5, p. 83.

Noble, D. C., 1962, Mesozoic geology of the southern Pine Nut Range, Douglas County, Nevada [Ph.D. dissert.]: Stanford, Calif., Stanford Univ., 251 p.

Ransome, F. L., 1899, Mother Lode district: U.S. Geol. Survey Geol. Atlas, folio 63, 11 p.

Rinehart, C. D., Ross, D. C., and Huber, N. K., 1959, Paleozoic and Mesozoic fossils in a thick stratigraphic section in the eastern Sierra Nevada, California: Geol. Soc. America Bull., v. 70, p. 941–946.

Schweickert, R. A., 1974, Probable late Paleozoic thrust fault near Sierra City, California: Geol. Soc. America Abs. with Programs, v. 6, p. 251.

Schweickert, R. A., and Wright, W. H., III, 1975, Preliminary evidence of the tectonic history of the Calaveras Formation of the western Sierra Nevada, California: Geol. Soc. America Abs. with Programs, v. 7, p. 371–372.

Sharp, R. V., and Duffield, W. A., 1973, Reinterpretation of the boundary between the Cosumnes and Logtown Ridge Formations, Amador County, California: Geol. Soc. America Bull., v. 84, p. 3969–3976.

Silberling, N. J., 1973, Geologic events during Permian-Triassic time along the Pacific margin of the United States, *in* Logan, A., and Hills, L. V., eds., The Permian and Triassic Systems and their mutual boundary: Calgary, Alberta Soc. Petroleum Geologists, p. 345–362.

Silberman, M. L., and McKee, E. H., 1971, Period of plutonism in north-central Nevada and southwestern Idaho: Econ. Geology, v. 66, p. 17–20.

Smith, J. G., McKee, E. H., Tatlock, D. B., and Marvin, R. F., 1971, Mesozoic granitic rocks in northwestern Nevada: A link between the Sierra Nevada and Idaho batholiths: Geol. Soc. America Bull., v. 82, p. 2933–2944.

Suppe, J., 1969, Times of metamorphism in the Franciscan terrain of the northern Coast Ranges, California: Geol. Soc. America Bull., v. 80, p. 135–142.

Suppe, J., and Armstrong, R. L., 1972, Potassium-argon dating of Franciscan metamorphic rocks: Am. Jour. Sci., v. 271, p. 217–233.

Taliaferro, N. L., 1942, Geologic history and correlation of the Jurassic of southwestern Oregon and California: Geol. Soc. America Bull., v. 53, p. 71–112.

Turner, H. W., 1893a, Some recent contributions to the geology of California: Am. Geologist, v. 11, p. 307–324.

——1893b, Mesozoic granite in Plumas County, California, and the Calaveras formation: Am. Geologist, v. 11, p. 425–526.

——1894a, Jackson, California: U.S. Geol. Survey Atlas, folio 6, 11 p.

——1894b, The rocks of the Sierra Nevada: U.S. Geol. Survey, 14th Ann. Rept., pt. 2, p. 435–495.

——1894c, Geological notes on the Sierra Nevada: Am. Geologist, v. 13, p. 228–249, 297–316.

——1895, The age and succession of igneous rocks of Sierra Nevada: Jour. Geology, v. 3, p. 385–414, map.

——1897, Downieville, Calif.: U.S. Geol. Survey Geol. Atlas, folio 37.

——1898, Bidwell Bar, Calif.: U.S. Geol. Survey Geol. Atlas, folio 43.

Turner, H. W., and Ransome, F. L., 1897a, Sonora, Calif: U.S. Geol. Survey Geol. Atlas, folio 41.

——1897b, Description of the Big Trees quadrangle: U.S. Geol. Survey Geol. Atlas, folio 51.

Manuscript Received by the Society October 21, 1974

Revised Manuscript Received February 20, 1975

Manuscript Accepted March 7, 1975