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TRIASSIC AND JURASSIC TECTONIC EVOLUTION OF THE KLAMATH MOUNTAINS-SIERRA NEVADA GEOLOGIC TERRANE

Pre-Mesozoic igneous, sedimentary, and metamorphic rocks in what are now the eastern Klamath Mountains and the northeastern Sierra Nevada constituted an island arc complex that evolved independently of the North American continent. During the Permo-Triassic Sonoma orogeny this complex became accreted to western North America after the oceanic basin that had separated it from the continent narrowed, then closed. No definitive plate models exist for the geometry of closure, but volcanic activity in the eastern Klamath Mountains was not, apparently, interrupted by the collision of Paleozoic arc and continental margin farther east. This relation argues for eastward subduction of oceanic lithosphere beneath the Klamath arc before, during, and after the collisional Sonoma orogeny.

The southwestern United States was affected by a tectonic event in earliest Triassic time that truncated abruptly all northeast-trending Paleozoic tectonic elements and stratigraphic trends (among them the Sierran portion of the Klamath-Sierran arc) and produced a new, northwest-trending continental margin. This event is postulated herein to have been the consequence of left-lateral transform faulting that shifted offset structural and stratigraphic elements to the southeast, presumably into northern Mexico. It is likely that the line of truncation did not extend as far northward as the Klamath Mountains, where the history of latest Permian through Middle Triassic volcanic activity appears to be essentially continuous.

By Late Triassic time the geologically diverse western margin of the continent from the southern Sierra into British Columbia had become the site of oblique (?) plate convergence, eastward subduction of Pacific Ocean lithosphere, and widespread arc magmatism. Oceanic rocks of late Paleozoic-early Mesozoic age and "Calaveras" ("Cache Creek" in Canada) lithology (cherts, argillites, and their ophiolitic basement) were accreted to the continental margin as a consequence of their incomplete subduction along it. A Late Triassic blueschist-grade assemblage of these rocks in the Fort Jones area of the Klamath Mountains probably predates the more extensive accretion of similar but lower-grade rocks of the Rattlesnake Creek and Hayfork-North Fork assemblages farther south in the Klamaths.

Some workers believe that western portions of the Klamath Mountains and Sierra Nevada are comprised of multiple Middle to Late Jurassic island arcs that were "swept" into and accreted against the continental margin during Jurassic plate convergence. Alternatively, we propose that the Middle and Late Jurassic igneous rocks of the two regions might have constituted portions of a *single* evolving arc that was constructed across the sutured plate boundary between the continent and allochthonous rocks of "Calaveras" type. Hence, eastern portions of the Jurassic arc were constructed on a basement of older continental arc rocks, whereas western portions were deposited on previously accreted rocks of oceanic affinity. Internal Middle (?) and Late Jurassic disruption and imbrication of this arc by strike-slip and thrust faulting is believed to have been an intraplate response to continued plate convergence to the west, not a direct expression of the collision and accretion to the continent of multiple arc complexes foreign to North America. The

trench and east-dipping subduction zone responsible for Jurassic arc magmatism lay to the west of the present Klamath-Sierran terrane, but it is doubtful that either has been preserved in the geologic record.

INTRODUCTION[1]

The pre-Mesozoic development of the Klamath Mountains-northern Sierra Nevada geologic terrane appears to have been geographically independent of continental North America until the time of the Permo-Triassic Sonoma orogeny. Prior to that time, igneous, metamorphic, and sedimentary rock assemblages in what are now the eastern Klamath Mountains and the northeastern Sierra Nevada comprised a Paleozoic ensimatic island arc that lay an unknown distance from the continental margin in central Nevada (Fig. 3-1). Boucot and Potter (1977) comment that some Ordovician, Devonian, and Permian faunal

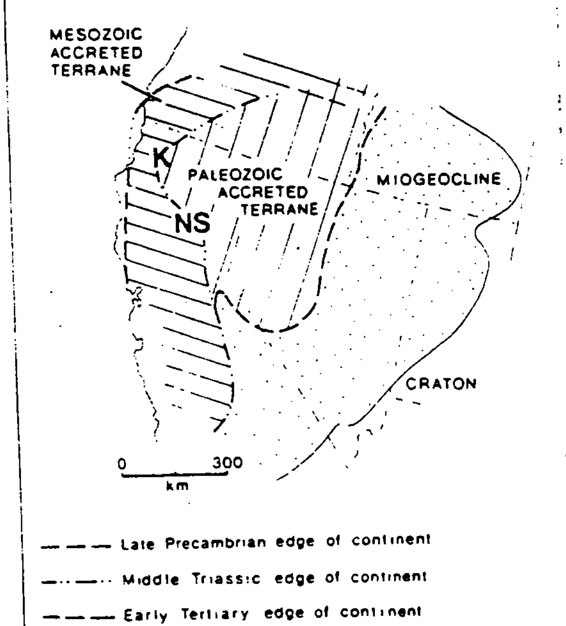

Fig. 3-1. Location of Klamath Mountains (K) and northern Sierra Nevada (NS) with respect to Paleozoic and Mesozoic accreted terranes in the southwestern United States.

[1] Portions of this paper were taken from a geographically more extensive treatment of Mesozoic Cordilleran tectonics by Davis and others (1978).

assemblages of the eastern Klamath Mountains have North American affinities, a relation that suggests relative proximity of the arc to the continent during its development. The Sonoma orogeny represents the collision and accretion of this offshore arc (or arcs) to the continent (Burchfiel and Davis, 1972; Silberling, 1973; Speed, 1974, 1977; see Dickinson, 1977, for a review of possible collisional geometries).

With accretion of the Klamath-Sierran arc by early Early Triassic time, the continental margin shifted abruptly westward from central Nevada to the western or outer side of the former island arc terrane (Fig. 3-1). Metavolcanic and metasedimentary rocks of the Klamath central metamorphic subprovince (Salmon Hornblende Schist and Grouse Ridge Formation) had previously been thrust (subducted) eastward beneath the eastern Klamath arc and its Trinity ophiolitic (?) basement in Devonian time (Burchfiel and Davis, 1972). Thus, following arc-continent collision at the time of the Sonoma orogeny, the outer edge of the arc (the new continental margin) lay somewhere west of presently exposed rocks of the central metamorphic subprovince.

In the eastern Klamath Mountains of northern California, sedimentary and volcanic rocks of Late Triassic (Karnian) and Middle Triassic age are described as lying in a conformable section above Late Permian and Early Triassic volcanic rocks (Dekkas Andesite, Bully Hill Rhyolite); the latter units, in turn, sit with only probable disconformity on sedimentary and volcanic rocks of Middle Permian age (Nosoni Formation). One can, therefore, infer essentially continuous magmatic activity in an eastern Klamath volcanic archipelago before, during, and after the Permo-Triassic orogeny in areas to the east. The tectonic accretion of the Paleozoic arc to the continent in Nevada did not apparently influence the volcanic history of the eastern Klamath subprovince. If the colliding arc and the Klamath-northern Sierran arc were one and the same, the continuity of volcanic activity in the Klamaths argues for *eastward* subduction of oceanic lithosphere beneath the Klamath arc from late Paleozoic into Jurassic time (for contrary interpretations, see Dickinson, Chapter 1, and Schweickert and Snyder, Chapter 7, this volume).

Burchfiel and Davis (1972, 1975) concluded that Permo-Triassic volcanic rocks in the eastern Klamath Mountains (Dekkas Andesite, Bully Hill Rhyolite) were the products of eastward subduction of ocean lithosphere beneath the arc, a geometry of ocean-arc convergence inherited at least from Siluro(?)-Devonian time. They concluded (erroneously) that the probable expression of this convergence is the east-dipping Siskiyou thrust fault, which separates upper plate rocks of the central metamorphic subprovince from lower plate "western Paleozoic and Triassic" units. The Siskiyou thrust fault is now known, however, to be of Jurassic age on the basis of recent field studies (Ando and others, 1977) and the occurrence of Jurassic radiolaria in lower plate rocks of the North Fork terrane (Irwin and others, 1978).

At the present time no candidate structures compatible with east-directed Permo-Triassic subduction beneath the Klamath segment of the arc are known, but the western edge of the arc where such structures might have been present has apparently not been preserved. Late Paleozoic-early Mesozoic (?) sedimentary and volcanic rocks of oceanic affinity that once lay outboard of the Paleozoic arc are probably present in the Fort Jones-Yreka area of the east-central Klamath Mountains, but such rocks do not appear to be widespread in the Klamath region. In the Fort Jones area a presently fault-bounded assemblage of chert, argillite, and mafic volcanic rocks was metamorphosed at considerable depth in Late Triassic time (214 to 222 m.y.a., K-Ar blueschist facies, Hotz and others, 1977). The assemblage may, therefore, be older than lithologically similar rocks exposed to the south in the central Klamath Mountains that Irwin and others describe as having been deposited on an ophiolitic basement of Late Triassic age (North Fork terrane; Irwin and others, 1977). In this latter area, exotic blocks of late Paleozoic carbonates, some containing a Tethyan fauna, are disconcertingly abundant in the Triassic-Jurassic chert-argillite sequence of the North Fork terrane. The Paleozoic source terrane(s) for these blocks is not known. It can be argued that the amount of Jurassic telescoping of Klamath rocks along the overlying Siskiyou thrust fault is extreme, and that the missing late Paleozoic oceanic assemblage (and adjacent trench?) at this latitude lies hidden to the east below the Siskiyou thrust plate. Alternatively, the former outer margin of the Permo-Triassic Klamath arc and rocks of the Pacific ocean basin adjacent to it may have been removed by the rifting or transform faulting that modified the early Mesozoic continental margin to the south (see following discussion).

CONTINENTAL TRUNCATION (POST-SONOMA OROGENY)

The northwest-trending early Mesozoic margin south of the Klamath Mountains (Fig. 3-1) appears not to coincide with the late Paleozoic outer edge of the accreted Klamath-Sierran arc. In central and southern California this margin truncates at a high angle the southwestward projections of all Paleozoic depositional ("eugeosynclinal," miogeoclinal, cratonal) and tectonic (Antler, Sonoma) trends (Figs. 3-2 and 3-3). This geometric relationship argues strongly for Early Mesozoic continental truncation by rifting or transform faulting, as originally proposed by Hamilton and Myers (1966) and schematically represented by Burchfiel and Davis (1972, their Fig. 7).

Schweickert (1976a) proposed that the truncated continental margin is defined by the Melones fault zone of the western Sierra Nevada, although as discussed later we consider the Melones to be a younger fault unrelated to the truncating fault zone. Nevertheless, in the northwestern Sierra, late Paleozoic (Devonian) volcanic rocks of the Klamath-Sierran arc and an older, metasedimentary basement (Shoo Fly Formation) lie directly east of the Melones fault (Fig. 3-3). To the west of the fault and bodies of ultramafic rock that are present along it, lies the "Calaveras Formation," a structurally disarrayed terrane of metacherts, phyllites, metavolcanic rocks, and serpentinized ultramafic rocks that Davis (1969) has correlated with lithologically similar rocks in the Klamath Mountains ("western Paleozoic and Triassic" subprovince). Here, then, the Melones fault does lie between rocks of the Paleozoic Klamath-Sierran arc and a western assemblage of oceanic rocks that is probably at least in part of younger age.

Within the central Sierra Nevada, however, the boundary between pretruncational rocks to the east and accreted rocks to the west is less clear. It certainly lies west of pendants in the eastern Sierran batholith (Log Cabin, Ritter Range, Mount Morrison, and

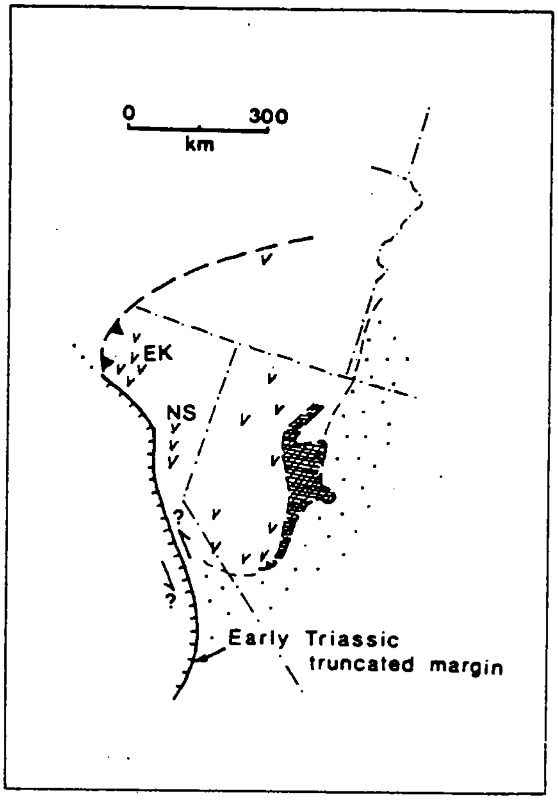

Fig. 3-2. Distribution of Upper Paleozoic rock assemblages with respect to Early Triassic truncated continental margin: clastic deposits related to Devono-Mississippian Antler orogeny (dots); ocean basin or marginal basin assemblage (cross-ruled pattern); volcanic arc rocks (V). EK, eastern Klamath Mountains; NS, northern Sierra Nevada.

Bishop Creek) that can be correlated with Paleozoic terranes of western Nevada (Speed and Kistler, 1977). The margin does not, however, appear to be coincident with the Melones fault, since here "Calaveras" rocks lie east of that fault, not west (Fig. 3-3). Chert-argillite units of the "Calaveras Formation" on both sides of the fault contain limestone lenses that have yielded scarce Permo-Carboniferous fossils, including Permian Tethyan fusulinids (Schweickert and others, 1977). We suggest that *all* "Calaveras" rocks must lie west of the truncated continental margin, and that in the central Sierra Nevada that margin lay east of the Melones fault zone (which must be a younger, unrelated structure) in a region now occupied largely by the Sierran batholith (Fig. 3-3). The "Calaveras Formation" is, in our opinion, a composite assemblage of remnants of one or more oceanic terranes. Older portions of the "formation" were carried into a subduction zone along the truncated margin and accreted to it in Middle or Late Triassic time. This exotic

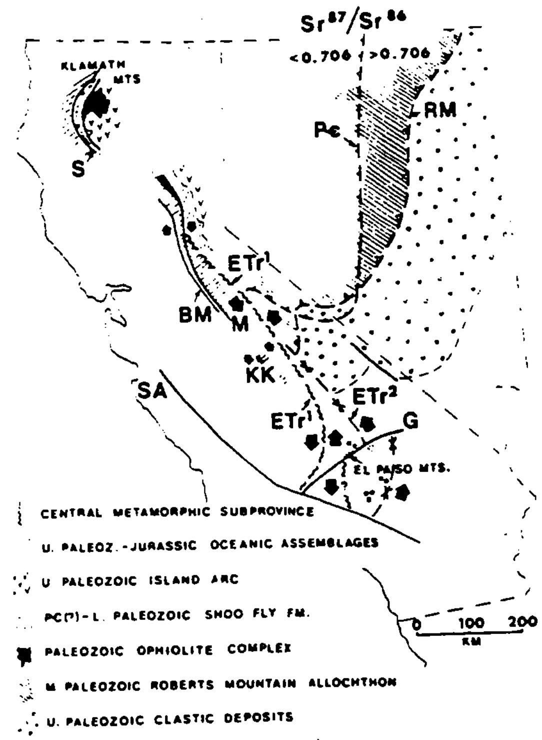

Fig. 3-3. Geologic relations across line of Early Triassic continental truncation. ETr^1, line of continental truncation and hypothesized transform fault with left slip; ETr^2, hypothesized inland fault related to ETr^1; P€, western limit of Precambrian crystalline basement rocks; RM, Roberts Mountains thrust fault of Devono-Mississippian age; S, Siskiyou thrust fault; BM, Bear Mountains fault zone; M, Melones fault; KK, Kings-Kaweah area; SA, San Andreas fault; G, Garlock fault.

oceanic assemblage includes the dismembered Kings-Kaweah ophiolite east of Fresno (Saleeby and others, 1978), which has been dated from plagiogranites as late Paleozoic (250 to 300 m.y., U-Pb, Saleeby, 1979).

The position of the line of truncation farther south is geologically even less definite, again in large part due to extensive Mesozoic plutonism. The plutons, however, themselves provide a clue to its location. Following Kistler and Peterman (1973), the west-to-east change in ^{87}Sr-^{86}Sr initial ratios in granitic rocks of the batholith from ⩽0.704 to ⩾0.706 appears to delineate the eastern edge of the accreted "eugeosynclinal" terrane and the westernmost extent of Precambrian crystalline basement. The position of this isotopic boundary, which is coincident in the Southern Sierra with ETr, is shown on Fig. 3-3. Early Paleozoic "eugeosynclinal" rocks that occur in the El Paso Mountains east of the boundary (and north of the Garlock fault) pose a problem to this interpretation. But very similar rocks lie east of the 0.706 line in central Nevada as well—in the Roberts Mountains thrust plate. We postulate that tectonic slicing along a truncated margin of transform type can explain these relations. The allochthonous (?) lower Paleozoic rocks and the upper Paleozoic clastic wedge sedimentary rocks deposited on them (Poole, 1974) may occur within a fault-bounded sliver east of the main transform boundary (Fig. 3-3). Offset of units in the hypothesized sliver from their initial position east of the zone of truncation is left-lateral. Perhaps the late Precambrian-early Paleozoic miogeoclinal section of the Caborca area, Sonora, Mexico, lies within another sliver, for it too is "out of place" in a left-lateral sense with respect to strikingly similar rocks in the Death Valley area. This suggestion is in accord with an earlier hypothesis of Silver and Anderson (1974), although the early to middle Mesozoic left-lateral fault that they proposed crosses the central Mojave Desert and is not coincident with that shown in Fig. 3-3. Van der Voo and others (1977) and Pilger (1978) present geologic arguments pertaining to the Gulf of Mexico region that are supportive of early Mesozoic sinistral fault displacement between the southwestern United States and Mexico. Both papers suggest that the truncated Antler orogenic belt may have been offset from southern California into mainland Mexico.

LATE TRIASSIC AND EARLY JURASSIC HISTORY

Different segments of the earliest Mesozoic continental margin of North America had different evolutionary histories. The margin appears to have been essentially accretional in areas north of the Klamath Mountains, but in southern areas the accreted Paleozoic arc and the continent itself had been subjected to faulting, apparently of transform type, that produced a truncated continental margin. Beginning in Late Triassic time, however, this geologically diverse margin became the site of similar magmatic, sedimentary, and metamorphic phenomena along its entire length, the consequence of oblique (?) convergence and subduction of Pacific Ocean lithosphere beneath the continent (Hamilton, 1969; Monger and others, 1972; Burchfiel and Davis, 1972). Convergence is recorded by widespread arc magmatism with initial ages of circa 220 to 195 m.y. (Late Triassic to Early Jurassic if the Triassic-Jurassic boundary is taken at 212 m.y.a.; R. Armstrong, in press), and by equally widespread and coeval ages for rocks of blueschist facies that lie west of the arc in oceanic rock assemblages (Fig. 3-4). The western margin of the continent was largely submerged, and the volcanic arc appeared as islands that supplied clastic detritus to adjacent basins. Marine basins that lay within or east of the arc were of epicontinental type. To the west of the volcanic archipelago lay a consuming trench, beyond which lay an ocean basin floored by upper Paleozoic and lower Mesozoic rocks of "Calaveras" lithology ("Cache Creek" in Canada).

Klamath Mountains, Oregon and California

Eastern Klamath arc Late Triassic through mid-Jurassic (Bajocian) volcanic arc activity is well preserved in the stratigraphic section of the eastern Klamath Mountains of northwestern California (Figs. 3-4, 6). Broadly correlative volcanic and sedimentary strata

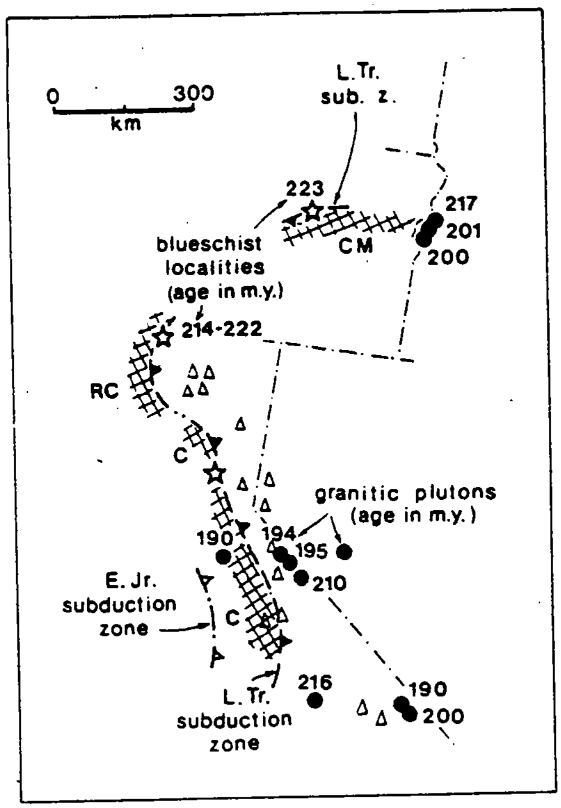

Fig. 3-4. Distribution of late Paleozoic through Early Jurassic oceanic rock assemblages of "Calaveras" lithology (cross-ruled pattern), and Late Triassic-Early Jurassic blueschist localities (stars), volcanic arc rocks (triangles), and granitic plutons (dark circles). C, "Calaveras" assemblages; RC, Rattlesnake Creek, Hayfork-North Fork, and Fort Jones area assemblages; CM, Canyon Mountain Complex, Burnt River Schist, Elkhorn Ridge Argillite.

occur to the south in the "eastern" belt of the Sierra Nevada (Schweickert and Cowan, 1975), where voluminous plutonic intrusion has obscured many initial stratigraphic relations. As mentioned previously, volcanic and sedimentary rocks of Late (Karnian) and Middle Triassic age in the eastern Klamath section sit with apparent conformity on Permo-Triassic rocks (Irwin, 1966). McMath (1966), however, reports that shelf-type carbonates of Late Triassic age (Norian; Hosselkus Limestone, Swearingen Formation) lie with angular unconformity on Permian and probable Permian pyroclastic and volcaniclastic strata in the Taylorsville area of the northern Sierra Nevada.

Rocks in the Klamath-Sierran arc are lithologically diverse and include andesitic lava, tuff, and breccia, siliceous pyroclastic rocks and ignimbrite, argillite, shallow-water limestone, and tuffaceous sandstone. No Late Triassic to mid-Jurassic granitic plutons occur in the Klamath portion of the arc, but a northwest-trending belt of 190 to 210 m.y. old plutons lies along the eastern margin of the Sierran batholith and extends into the eastern Mojave Desert (Fig. 3-4). The discontinuous belt parallels the truncated early Mesozoic margin of the continent and crosscuts older, northeast-trending stratigraphic and structural elements (Burchfiel and Davis, 1972).

Western oceanic assemblages An open ocean basin lay somewhere west of the eastern Klamath arc in Late Triassic and Early Jurassic time. Eastward subduction of oceanic lithosphere beneath the arc is implied by the magmatic activity of the arc and by the occurrence along its present northwestern margin of an allochthonous blueschist terrane of appropriate age (222 to 214 m.y., Hotz and others, 1977). The present structural setting of the blueschists near Fort Jones may or may not, however, date from the time of Late Triassic convergence. Field relations in areas to the south (subsequently treated) suggest that major thrust faulting in the Fort Jones area may be of Jurassic age.

Triassic oceanic crust west of the eastern Klamath and central metamorphic subprovinces may be represented by at least two ophiolitic sequences in the "western Paleozoic and Triassic" subprovince. Identified by Irwin (1972) as the North Fork and Rattlesnake Creek terranes (Fig. 3-5), they lie along the eastern and western margins of the subprovince respectively in areas south of 41°15′N latitude. Irwin has also defined a centrally located lithologic assemblage, the Hayfork terrane, which Ando and others (1977) consider to be largely correlative with sedimentary and volcanic rocks of the North Fork terrane. The Preston Peak ophiolite (Snoke, 1977) lies along the western edge of the subprovince just south of the Oregon border. It may be a northern equivalent of either the ophiolitic Rattlesnake Creek or North Fork terrane, although its age and geologic relations with these terranes is not known.

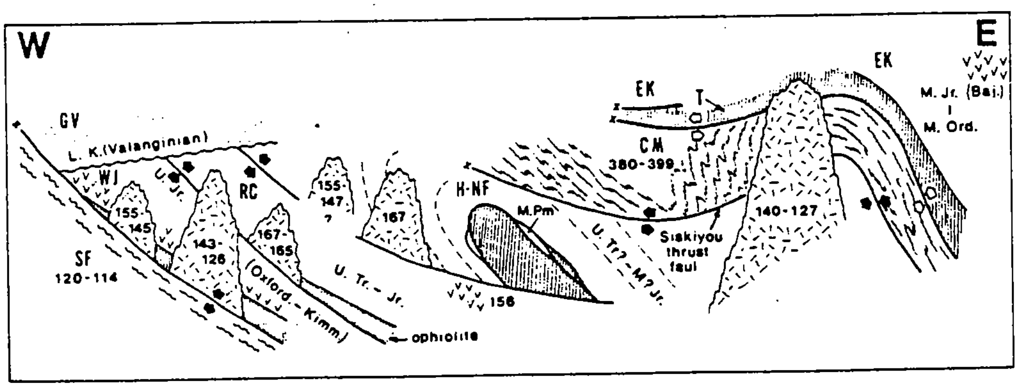

Fig. 3-5. Diagrammatic representation of stratigraphic and radiometric age controls on thrust faulting in the Klamath Mountains, California and Oregon. Length of section is approximately 200 km. SF, South Fork Mountain Schist; GV, Great Valley Sequence; WJ, western Jurassic subprovince; RC, Rattlesnake Creek terrane; H-NF, Hayfork-North Fork terrane; CM, central metamorphic subprovince, T, Trinity ophiolite; EK, eastern Klamath subprovince. Thrust faults with black relative motion arrows are post-Paleozoic in age. Radiometric age data from Hotz (1971), Dick (1973), Young (1974), Lanphere and others (1975), Snoke (1977), and Irwin (1977).

The North Fork ophiolite is tectonically dismembered and lacks the sheeted dike complex characteristic of many other ophiolites. Gabbro exposed in the core of a regional north-plunging antiform (between the Salmon and Trinity Rivers) grades abruptly upward into fine-grained diabase of hypabyssal character (Ando, *in* Ando and others, 1977). Sheetlike units of serpentinized peridotite (North Fork and Twin Sisters bodies) are tectonically interleaved between core gabbro and diabase and structurally higher pillow basalt, chert, and volcaniclastic rocks. Irwin and others (1977) report that radiolarians from red chert "associated with the ultramafic-mafic rocks of the ophiolite" in an area south of the Trinity River are probably Late Triassic. However, southwest of Cecilville, mid-Permian (Wardian) radiolarians and conodonts were found in a block of red chert that lies structurally between the ophiolitic core of the North Fork antiform and the stratigraphic sequence that constitutes its eastern flank (Fig. 3-5; Irwin and others, 1978). The age of the North Fork ophiolite in this area is, therefore, open to question.

North Fork strata in the eastern flank of the antiform include altered mafic volcanic and pyroclastic rocks that appear to lie depositionally above rhythmically bedded cherts and are, in turn, overlain unconformably by shallow-water limestones. Rounded cobbles of metabasalt are present in basal layers of the limestone, which is itself overlain by more rhythmically bedded chert (Davis, 1968). Samples apparently collected from this upper chert unit yield radiolarians of Late Triassic age (Irwin and others, 1978, localities 8, 9, and 10). This stratigraphic sequence is indicative of the growth on the ocean floor of a seamount, its emergence and erosion as an oceanic island, and its subsequent subsidence, all before the deposition of Late Triassic cherts. Exotic blueschist blocks with a lawsonite-glaucophane-(jadeite) mineralogy (E. Ghent, written communication, 1977) occur in a poorly exposed chaotic (olistostromal?) zone (Davis, 1968). The blocks are undated, but some resemble mineralogically the Fort Jones area blueschists, and a 220 m.y. initial age for them seems likely. They are present on both flanks of the North Fork antiform (Fig. 3-5), in the North Fork section to the east and the Hayfork section to the west. This relation supports the equivalency of the "two" terranes (Ando and others, 1977), although a regional east-dipping thrust fault between Hayfork units and the ophiolitic core of the North Fork antiform cannot yet be disproved.

The relation of the North Fork-Hayfork and Rattlesnake Creek ophiolitic terranes to each other is also not clear, although both appear to be essentially coeval (cherts in both have yielded Late Triassic and Jurassic radiolaria). Irwin (1972), however, has previously indicated that the fauna from carbonate pods in the two terranes (now interpreted as exotic blocks) are markedly different and almost mutually exclusive; the Rattlesnake Creek terrane is characterized by a coral-like chaetetid fauna, the North Fork-Hayfork by a fusulinid fauna. Possible paleogeographic relations between the eastern Klamath arc and the North Fork and Rattlesnake Creek oceanic terranes are discussed later, since faults that presently separate these lithologic assemblages are probably all of Late Jurassic age.

Sierra Nevada

The "Calaveras Formation" of the western Sierra Nevada appears to be in part a southern counterpart of the North Fork-Hayfork and Rattlesnake Creek Mesozoic ophiolitic terranes (Davis, 1969). Irwin and others (1978) report the occurrence of Triassic or Jurassic radiolaria in cherts mapped as "Calaveras" in the northern Sierra Nevada. However, the presence of the Late Paleozoic Kings-Kaweah ophiolite in the southwestern Sierra Nevada (Fig. 3-3) upon which Calaveras-type olistostromes were "deposited" (Saleeby and others, 1978) indicates that pre-Mesozoic oceanic rocks are also a component of the accreted terrane. In this southern area a Late Permian Tethyan fusulinid fauna has been collected from the "Calaveras" rocks, specifically from a limestone block in a chert-argillite olistostromal unit (Schweickert and others, 1977). This unit is overlain by continent-derived quartzitic strata of Late Triassic and Early Jurassic age, which are in turn overlain by felsic volcanic rocks. Metamorphic tectonites derived from mafic members of the ophiolite yield K-Ar ages of 190 m.y., an Early Jurassic age considered by Saleeby to be the likely age for emplacement of the ophiolite against the continent. Geologic relations described by Saleeby lead us to the following conclusions: (1) the original truncated margin lies east of all "Calaveras" rocks in the Kings-Kaweah area (Fig. 3-3); (2) late Paleozoic "Calaveras" rocks and their ophiolitic basement were brought against that continental margin following the initiation of Middle to Late Triassic plate convergence along it; (3) subsequent shifting of the zone of convergence to the west of the accreted oceanic terrane was followed, in Early Jurassic time, by its internal disruption along a major strike-slip fault zone (the Kings-Kaweah "suture"); (4) this zone was parallel to an active trench to the west, and its existence implies oblique convergent motion along that plate boundary (Saleeby and others, 1978); and (5) Late Triassic and Early Jurassic sedimentary and volcanic rocks that depositionally overlie western "Calaveras" units (and were also offset by transcurrent faulting) may conceal the older truncational boundary in areas to the east.

Despite convergent accretion of some or all of the "Calaveras" terrane in the Triassic period, Upper Triassic and lowest Jurassic strata in the Sierra Nevada appear to record a time of relative arc inactivity, in contrast to the eastern Klamath Mountains. A number of Sierran stratigraphic sequences of this age are nonvolcanic or, at best, contain only minor contributions from volcanic sources (Schweickert and Cowan, 1975). This relationship is surprising, since scattered eastern Sierran plutons have ages that fall in a Late Triassic-Early Jurassic time period (220 to 190 m.y.) and do attest to at least sporadic magmatic activity within the newborn arc (Fig. 3-4). During later Early Jurassic time, Andean-type magmatism in the Sierran region was evidently more widespread. Thick sequences of volcanic rocks dating from this time are present in the northeastern and east-central Sierra Nevada (Stanley and others, 1971, Fig. 4). Saleeby (1977a) has suggested that in the southern Sierra Nevada, arc volcanism spread far enough westward that Lower Jurassic volcanic rocks and sediments derived from the older "Calaveras" terrane were deposited on top of the ophiolitic complex of the Kings-Kaweah area. Thus, by Early Jurassic time subduction at this latitude had apparently stepped westward from its Middle to Late Triassic position.

The volcanic rocks that lie west of the Melones fault zone in the Sierran foothills have generally been regarded as Middle and Late Jurassic in age (Schweickert and Cowan, 1975), but the studies of Saleeby cited previously and Morgan and Stern (1977) suggest that older volcanic (and plutonic) rocks are also present in the western Sierra Nevada. Morgan and Stern (1977) report that a small pluton near Sonora yields a U-Pb age of

190 m.y. (Early Jurassic). It intrudes alpine-type ultramafic rocks and unconformably overlying Peñon Blanco volcanic rocks (Fig. 3-4) that occur west of the Melones fault zone and east of the Bear Mountains fault zone. Although the mafic Peñon Blanco volcanic rocks (lava, breccia, tuff) may be oceanic in affinity rather than an expression of arc activity, the pluton that intrudes them is indicative of surprisingly early plutonism in this terrane.

The ages of metavolcanic and metatuffaceous rocks (Franklin Canyon and Duffey Dome formations) that occur between the Melones and Bear Mountains fault zones in the northernmost Sierra Nevada and lie unconformably above deformed "Calaveras" cherts, phyllites, and discontinuous limestone bodies are not known (Fig. 3-3). Hietanen (1973) tentatively correlates them with late Paleozoic units of the Klamath-Sierran arc to the east of the Melones fault. We believe that a Mesozoic age assignment is more likely, since these metavolcanic rocks reportedly overlie unconformably an accreted "Calaveras" terrane in a manner comparable to relations described by Saleeby far to the south, and because we consider it unlikely that *any* rocks of the Paleozoic Klamath-Sierran volcanic arc are preserved west of the Melones fault. Hietanen (1977) does report that lower-grade metavolcanic rocks of variable composition (mafic augite basalt, andesite, dacite, soda-rhyolite) and probable Late Jurassic age (Bloomer Hill Formation) overlie phyllites of unknown age north of Lake Oroville. The phyllites are extensions of an undifferentiated "Calaveras" unit mapped by Creely (1965) in the Oroville quadrangle to the south, where a Late Triassic (?) ammonite was collected from overlying strata that includes metavolcanic rocks.

MIDDLE AND LATE JURASSIC HISTORY

Klamath Mountains

The Klamath Mountains of northwestern California and southwestern Oregon are a geologic continuation to the northwest of the Sierra Nevada (Davis, 1969; Hamilton, 1969). This point has been discussed previously in terms of correlative early Mesozoic and late Paleozoic arc and oceanic rock assemblages in the two geographic areas (Figs. 3-2 through 3-4). Most of the Klamath Mountains province west of the Siskiyou thrust fault and much of the Sierra Nevada province west of the Melones fault consist of Jurassic sedimentary and igneous rocks with both arc and oceanic affinities. With the advent of plate tectonics, an increasing number of authors have interpreted the Jurassic rocks of the western Klamath Mountains and Sierra Nevada as exotic elements of the Cordillera, that is, units alien to the North American plate but carried to it atop Pacific Ocean lithosphere that was subducted in Jurassic time along the western edge of the continent.

Hamilton (1978a, p. 46), for example, states that the Klamath Mountains west of the central metamorphic subprovince consist of "variably aggregated island-arc fragments, perhaps analogous to the southern Philippine Islands" (where he interprets a tectonic assemblage of at least six different Cenozoic island-arc systems). The multiple Klamath island arcs are considered by him to have been "individually active during Middle and

Late Jurassic time, and probably earlier" (ibid.). Similarly, Dickinson (1976, p. 1275) concludes that the western Sierra Nevada is a Jurassic subduction complex consisting of "scraps of intraoceanic island arcs of early Late Jurassic and older (?) age with melanges and ophiolitic slices of uncertain but presumably similar age." Both Hamilton (1978a) and Dickinson (1976), among others (e.g., Moores, 1972; Schweickert and Cowan, 1975), regard Middle and Late Jurassic magmatic activity in the western part of the Klamath-Sierra terrane as distinct from and geographically separated from coeval Jurassic magmatic activity in the eastern Klamaths and Sierra Nevada.

It is our opinion that such hypotheses are increasingly difficult to defend as mapping studies in the western Klamath and Sierran regions progress. In the following sections on the two areas we attempt to develop an alternative concept. Specifically, we propose that the Middle and Late Jurassic igneous rocks of the two regions constitute portions of a *single* complex arc that was constructed across a previously sutured [Middle Triassic to Early (?) Jurassic] plate boundary between western oceanic rocks of "Calaveras" type and the continent. We present evidence that major Jurassic faults within this Klamath-Sierra arc are not former sutures or plate boundaries along which multiple exotic arcs collided, but are instead intraplate faults that developed within the evolving arc. The test of our alternative hypothesis, as well as that of contrasting interpretations, will come from additional field, paleontologic, and paleomagnetic studies in these important terranes.

As Figures 3-5 and 3-6 illustrate, the record of Middle and Late Jurassic volcanic and plutonic activity in the Klamath Mountains and northern Sierra Nevada is widespread. In the eastern Klamath Mountains, Mesozoic volcanic activity continued until at least the Bajocian (Middle Jurassic); younger Mesozoic volcanic units, if once present, may lie hidden beneath an eastern cover of Cenozoic Cascade volcanic rocks. Callovian and younger (?) strata in the northeastern Sierran Nevada are present and indicate continuation of Mesozoic volcanic arc activity there into the Late Jurassic. The basement for this eastern, arc-related activity was the ensimatic island arc of Paleozoic age that had been accreted to the continent during the Sonoma orogeny.

Farther west, Charlton (1978; personal communication, 1978) reports that hemipelagic sediments and volcaniclastic rocks correlative with the Hayfork Bally Meta-andesite of Irwin (1977) lie depositionally on pillow basalts that he tentatively assigns to the Rattlesnake Creek ophiolite. Nearby meta-andesites are intruded and deformed by the Ironside Mountain batholith (165 to 167 m.y., Lanphere and others, 1968).

Still farther west, Late Jurassic rocks [Callovian (?), Oxfordian, and Kimmeridgian] in the Klamath Mountains are well represented by the Galice Formation, a unit of phyllite, slate, and semischist (Fig. 3-5) of the western Jurassic subprovince. At most localities the metasedimentary rocks are intercalated with and overlie metavolcanic and metapyroclastic rocks of intermediate to silicic composition (the Rogue Formation in northernmost California and southwestern Oregon). Near O'Brien, Oregon, Vail and Dasch (1977) report that Galice slate and graywacke depositionally overlie pillowed spilite of the Jurassic Josephine ophiolite. Late Jurassic plutons ranging in age from 155 to 140 m.y. intrude the Rogue and Galice formations and mafic and ultramafic rocks assigned to the Josephine ophiolite in both Oregon (Hotz, 1971; Dick, 1973) and California (Young, 1974). At the present time, all these Jurassic units (sedimentary, volcanic, plutonic) lie in the upper

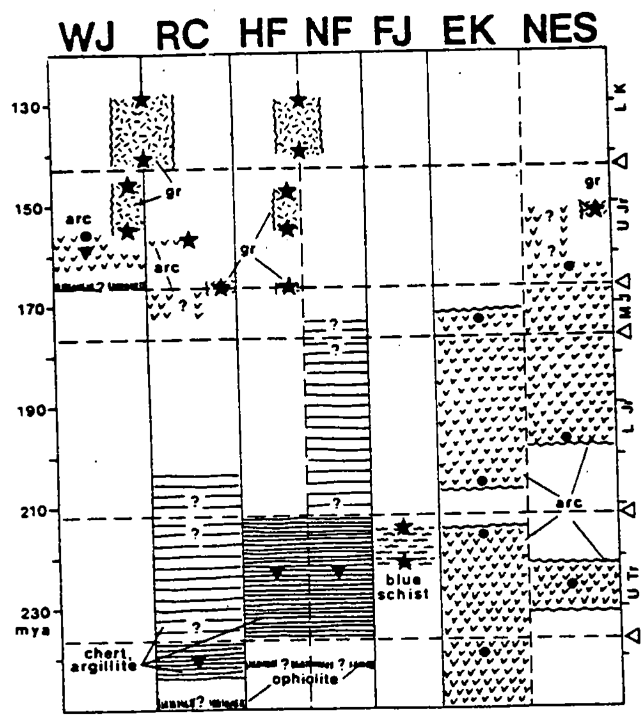

Fig. 3-6. Mesozoic paleogeographic assemblages and intervals of plutonic activity, Klamath Mountains and northeastern Sierra Nevada. Geologic terranes represented by columns, from west to east: WJ, western Jurassic subprovince; RC, Rattlesnake Creek terrane; HF, Hayfork terrane; NF, North Fork terrane; FJ, Fort Jones area blueschist terrane; EK, eastern Klamath subprovince; NES, northeastern Sierra Nevada. Age control: radiometric dates (stars); megafossils (closed circles); radiolaria (closed triangles). References for radiometric dates listed in caption for Fig. 3-5.

plate of a regional thrust fault above Tithonian and younger Franciscan rocks (in Oregon, Dothan) of the Coast Ranges.

The western Jurassic, Rattlesnake Creek, North Fork-Hayfork, and eastern Klamath volcanic and sedimentary assemblages are now all separated from each other by major east-dipping thrust faults (as diagrammatically represented in Fig. 3-5). Geologic and geochronologic data bracket each of the three separating faults rather closely. The lower two (between western Jurassic, Rattlesnake Creek, and North Fork-Hayfork terranes) are almost certainly Late Jurassic in age. The higher Siskiyou thrust fault could conceivably be somewhat older (Middle or Late Jurassic) because of the uncertainties concerning the age of the youngest rocks to be found in the underlying North Fork terrane.

If, as Hamilton (1978a) has suggested, the Middle and Late Jurassic magmatic activity of the western Jurassic, Rattlesnake Creek, and eastern Klamath regions occurred within independent, separately evolving arcs (the first two oceanic), then the fault boundaries that now separate them must represent sutures between major plate elements.

None of these three faults, however, can be identified with certainty as a convergent plate boundary at the time of its formation, and at least one, the Siskiyou thrust, is an intraplate fault that crosscuts older structures in both upper and lower plates (Fig. 3-5; Davis, 1968; Ando and others, 1977).

Geologic relations suggest that the Middle and Late Jurassic volcanic rocks and coeval plutons in the Klamath Mountains could be components of a single, evolving magmatic arc that was constructed across a previously sutured ocean-continent boundary and was related to eastward subduction along a western trench that has not been preserved. Although an east-dipping Late Triassic or Early Jurassic subduction zone probably once separated the North Fork oceanic terrane from the continental plate to the east, the presently intervening Siskiyou thrust fault does not appear to be a direct expression of such an inferred plate boundary. As mentioned previously, the Siskiyou thrust is younger than episodes of low-angle faulting, major antiformal folding, greenschist facies regional metamorphism, and, possibly, Middle Jurassic granitic intrusion into rocks of the North Fork-Hayfork lower plate.

It might be argued that a consuming plate boundary is represented by the thrust fault that separates the North Fork-Hayfork and Rattlesnake Creek terranes, the latter with its Ironside Mountain batholith–Hayfork Bally Meta-andesite arc components (as interpreted by D. Charlton). However, geologic relations favor the interpretation that this fault, too, is the consequence of intraplate shortening. The hanging wall Hayfork-North Fork terrane is intruded by a Middle Jurassic pluton (Forks of Salmon) that is identical in age (167 m.y., K-Ar) and similar in composition (syenodioritic) to the footwall Ironside Mountain pluton (Hotz, 1971). Thus coeval plutonism appears to have affected both of the ophiolitic terranes prior to the period of thrust faulting that now juxtaposes them. The possibility that detritus from the Rattlesnake Creek-Hayfork Bally Meta-andesite "arc" is present in Hayfork strata (D. Charlton, personal communication, 1978) may be supplemental evidence that the two terranes were in proximity during Early to Middle Jurassic time.

The paleogeographic setting of the Rogue-Galice assemblage is admittedly uncertain, but the presence of heavy detrital minerals in Galice graywackes (including glaucophane, hornblende, garnet, tourmaline, epidote, and zircon; Harper, 1978) may indicate that Galice sediments were derived from older Klamath crystalline rocks, were deposited near the North American continental margin, and may not have been separated from the continent by an intervening oceanic trench. It is, therefore, difficult to visualize the Rogue-Galice assemblage as being a far-traveled and exotic component of the Cordillera. As discussed in a later section, a similar conclusion can be drawn for the Logtown Ridge-Mariposa sequence of the western Sierra Nevada, with which the Rogue-Galice sequence has often been correlated.

It is, nevertheless, conceivable that the east-dipping regional thrust fault that now separates footwall rocks (Josephine ophiolite-Rogue-Galice) from higher lithological assemblages (Rattlesnake Creek and Preston Peak) represents a fundamental Late Jurassic plate boundary, particularly since the Josephine and Rattlesnake Creek ophiolites appear to be of considerably different ages (Jurassic and Triassic, respectively). However, in the context of Klamath plutonism it is difficult to view this thrust fault as being other than an intra-arc (intraplate) structure. The thrust postdates strata in the Galice Formation as young as early Kimmeridgian, but it is intruded by plutons of latest Jurassic-earliest Cretaceous ages (ca. 143 to 126 m.y., K-Ar, Snoke, 1977). Plutons of somewhat older age intrude both footwall Rogue-Galice rocks (155 to 145 m.y., K-Ar, Hotz, 1971; Dick, 1973; Young, 1974) and hanging wall rocks of the "western Paleozoic and Triassic" subprovince (155 to 147 m.y., Hotz, 1971). Unfortunately, their age relation to thrust faulting is not known. Since some of the plutons have ages that fall within the Kimmeridgian stage (ca. 157 to 150 m.y., Armstrong, in press) they may be essentially contemporaneous with Rogue-Galice volcanism and, therefore, older than thrusting. More stratigraphic and radiometric age data obviously are needed, but the data reviewed here raise the distinct possibility that Late Jurassic and Early Cretaceous plutons were emplaced respectively before *and* after thrust faulting into rocks of both the western Jurassic and "western Paleozoic and Triassic" subprovinces.

The most reasonable interpretation of these relationships (Fig. 3-5) is that thrusting between the two subprovinces occurred *within* a Late Jurassic-Early Cretaceous magmatic arc, not along a plate boundary. If the widespread Late Jurassic-Early Cretaceous magmatism is related to subduction of oceanic lithosphere beneath the arc, then the convergent plate boundary (trench) lay considerably west of present exposures of Rogue-Galice rocks. Since Late Jurassic and Middle Jurassic plutons are spatially superimposed in the western Klamath Mountains, the possibility exists that all are related to the same east-dipping subduction system.

Collectively, the spatial and temporal relationships between Klamath plutonism and thrust faulting described here indicate that an evolving Middle and Late Jurassic arc complex was internally disrupted and telescoped by Middle (?) to Late Jurassic faulting. This deformation can be tied to the effects of plate convergence between ocean basin and arc, as can of course the widespread Jurassic volcanism and plutonism. This idea, which is amplified in the succeeding section on the Sierra Nevada, is admittedly conservative, but we suggest that it is philosophically at least as satisfying as concepts currently in vogue that three (or more) separate and independently evolving Jurassic volcanic arcs, or their remnants, are now preserved in the narrow, 200-km wide Klamath terrane.[2] Figure 3-7 supports these conclusions. Three separately evolving Jurassic arcs are shown (Fig. 3-7a) without vertical exaggeration prior to their collision and aggregation as postulated by others. Dips of 45° for the three subducting plates were selected to reduce arc widths to geologically conservative values. The arcs pictured include a western Jurassic arc with a Jurassic ophiolitic basement (Josephine), a Rattlesnake Creek arc with an early Mesozoic basement of "Calaveras"-type oceanic rocks, and an eastern Klamath-northeastern Sierra arc with a basement of older Mesozoic continental arc rocks. Figure 3-7b illustrates the present configuration of the thrust-fault-bounded Klamath subprovinces at the same scale for comparison. The space and scale problems implicit in this illustration of a multi-Jurassic arc origin (Fig. 3-7a) for the present Klamath province (Fig. 3-7b) are so extreme that a simpler explanation appears to be necessary.

[2]For comparative purposes, the Cenozoic Aleutian arc is 210 km wide at 176°W longitude (from trench axis to the abyssal floor of the Aleutian Basin).

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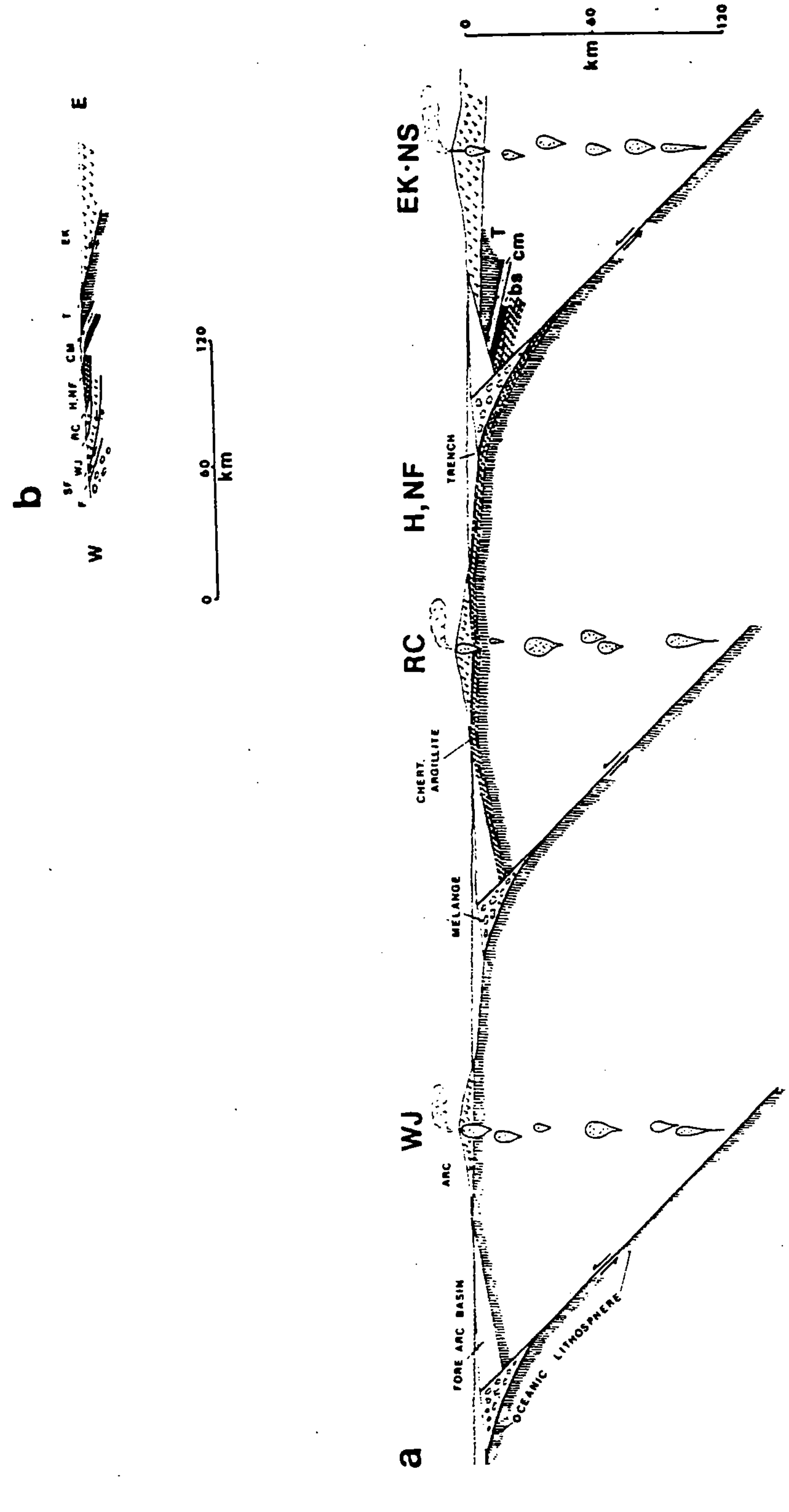

Fig. 3-7. (a) Hypothetical cross section through active, multiple Klamath volcanic arcs in early Late Jurassic time prior to their collision and aggregation (no vertical exaggeration). WJ, western Jurassic island arc; RC, Rattlesnake Creek island arc; H, NF, Hayfork, North Fork oceanic terrane; EK-NS, eastern Klamath-northern Sierra Nevada continental margin arc. Basement for the latter includes: T, Trinity ophiolitic complex (Ordovician?); cm, central metamorphic subprovince (Devonian); bs, blueschist assemblage of type exposed near Fort Jones (Late Triassic). (b) Highly simplified, essentially true scale geologic cross section through central Klamath Mountains, California (plutons omitted). F, Franciscan Complex; SF, South Fork Mountain Schist; other letter designations as in Fig. 3-7a.

Sierra Nevada

Middle Jurassic through Early Cretaceous volcanism and plutonism are well documented in the geologic record of the eastern Sierra and western Nevada. This magmatic activity is representative of an Andean-type arc formed along the leading edge of the North American plate. However, as in the Klamath Mountains, broadly coeval volcanism and plutonism occurred in areas west of what many consider to be the main, continental margin arc. In the case of the Sierra Nevada, these igneous rocks lie west of the Melones fault zone and correlate, in part, with the Rogue-Galice assemblage of the western Jurassic Klamath subprovince. Their plate tectonic setting is controversial. They have recently been interpreted (Schweickert and Cowan, 1975) as exotic components of the Cordilleran Orogen that include from east to west, an ensimatic east-facing island arc, an interarc basin floored by oceanic crust, and a remnant arc split from the main arc to the east. Collision of the east-facing island arc with the west-facing Sierran continental arc is purported to have occurred along the Melones fault, an arc-continent suture of Late Jurassic age. The Bear Mountain fault zone to the west represents a zone of partial collision of the remnant arc with its eastern "parent" arc.

This interpretation is troubling to us for a number of reasons, some of them reminiscent of Klamath Mountain problems discussed previously, but largely independent of them. In the western Sierra Nevada the Smartsville ophiolite is bordered on the east and west by Schweickert and Cowan's Jurassic island arc and remnant arc, respectively. They tentatively interpret the Jurassic ophiolite as the oceanic floor of an interarc basin, formed during rifting of the remnant arc from its parent. The ophiolite, however, has an antiformal structure, and studies by E. Moores and his associates (Bond and others, 1977; Buer, 1977; Xenophontos and Bond, 1978) indicate that flanking Middle and Upper Jurassic volcanic and sedimentary rocks were deposited upon the ophiolite, not separated by it. Another problem with the rifted interarc basin paleogeography of Schweickert and Cowan is that their western (remnant) and eastern (island) arcs are separated near the Consumnes River by a melange belt (Duffield and Sharp, 1975) that contains rocks of "Calaveras" lithology, including limestone blocks bearing a Tethyan Permian fusulinid fauna (Douglass, 1967). This relation is difficult to explain if the hypothesized interarc basin formed by the Jurassic rifting of a Jurassic ensimatic island arc.

The relationships between Mesozoic volcanic and sedimentary rocks in the Sierran Foothills and older oceanic rocks of Calaveras-type are interesting. Saleeby's studies (1977a; Saleeby and others, 1978) between the Kings and Kaweah rivers in the southwestern Sierra Nevada indicate that "Calaveras" rocks accreted to the continent are overlain by continent-derived sedimentary rocks of Late Triassic age and by Early Jurassic volcanic rocks that can be related to a more westerly, east-dipping subduction zone. The location of the Kings-Kaweah area with respect to the Melones fault zone to the north is not definite, but Saleeby believes that it is a southern extension of eastern portions of the Sierran Foothills terrane. If so, Jurassic volcanic rocks and somewhat younger plutons that lie west of the Melones fault were part of the continent in Jurassic time and cannot be exotic with respect to North America.

At the opposite, northern end of the Sierra Nevada, Hietanen (1973) and Creely

(1965) have also concluded that "Calaveras" rocks west of the Melones fault zone form the basement for Mesozoic volcanic rocks. For example, volcanic rocks of Logtown Ridge (= Rogue Formation?) lithology and age overlie "Calaveras" phyllites in the vicinity of Oroville (east of the Smartsville ophiolite), although studies in progress at the University of California, Davis, suggest that the contact may be a low-angle fault (E. Moores, personal communication, 1978). Elsewhere in the Sierran Foothills some lithic clasts in Mariposa (= Galice Formation?) graywackes were derived from a "Calaveras"-type source terrane (Behrman and Parkison, 1978). Others were derived from older Paleozoic units (including the Shoo Fly Formation) that lie east of the Melones fault and were part of continental North America at the time of Mariposa sedimentation (R. Schweickert, personal communication, 1978).

In central parts of the Foothills belt, the relationship described by Duffield and Sharp (1975), that a Calaveras-type "melange" along the Bear Mountains fault zone separates similar Jurassic volcanic terranes, could also be explained by the initial deposition of volcanic rocks atop a previously disrupted "Calaveras" basement. As Schweickert and Cowan (1975) point out, it is extremely significant that no fragments of the adjacent (overlying?) volcanic rocks (Logtown Ridge Formation) occur within the melange. Schweickert (1978, p. 373) has since concluded that Jurassic volcanic rocks west of the Melones fault were deposited on "a structurally complex assortment of slices of oceanic crust, melanges, and sheets of ultramafic rock that evidently were deformed and juxtaposed prior to the birth of the island arc." He also states that chaotic chert-argillite units in the complex basement resemble the "Calaveras Complex." The location of this complex, deformed basement at the time of Jurassic volcanism atop it is of extreme importance to an understanding of Sierran Mesozoic tectonics. Schweickert believes that the basement terrane lay an unknown distance west or southwest of the west coast of North America at the time an island arc was being constructed on it.

Alternatively, we believe that it represents a subduction zone complex that had already been accreted onto the western edge of the continent by Late Triassic or Early Jurassic (?) time. We postulate that Early (?), Middle, and Late Jurassic volcanic and plutonic rocks in the western and eastern Sierra Nevada (as in their Klamath counterparts to the north) belong to one magmatic arc complex that was built across a previously sutured (Middle to Late Triassic) convergent plate boundary. East of the boundary, the Jurassic arc was constructed on an older basement terrane that included the Late Triassic Sierran arc and older lithotectonic elements (from northwest to southeast, the Paleozoic Klamath-Sierran arc, Antler and Sonoma allocthonous units, the miogeoclinal prism, and cratonal basement and cover). Directly west of the boundary the arc was built on accreted late Paleozoic and early Mesozoic oceanic rocks of the "Calaveras" terrane (equivalent to Hayfork-North Fork and Rattlesnake Creek assemblages farther north). Still farther west, its basement was at least locally relatively undisturbed ocean crust of unknown origin—the Smartsville ophiolite (possibly comparable to the Josephine ophiolite of the western Klamath Mountains). Similar, independently arrived at conclusions have recently been drawn for the Sierra Nevada by Behrman and Parkison (1978) and by Saleeby and others (1978).

The arc did not develop statically across the diverse basement terranes just cited.

Marine sedimentation, volcanic activity, and plutonic intrusion were accompanied, as in the Klamath Mountains, by profound internal disruption and imbrication of the evolving arc by strike-slip and thrust faulting. Saleeby's Kings-Kaweah "suture" is certainly the best documented example of the former. Displacement along this zone of transcurrent faulting began roughly 190 m.y. ago and continued until at least the Late Jurassic, as indicated by a 157 m.y. concordant U-Pb zircon age for a synkinematic intrusion pluton emplaced across it (Saleeby, 1977a, 1977). To the north, the Melones fault zone, which may be a component of the Kings-Kaweah "suture," disrupts a 162 m.y. old diorite stock; movement along it appears to have ceased by 140 m.y. ago (Morgan and Stern, 1977).

Relationships between the steep, east-dipping faults of the western Sierra and the low-angle, east-rooting thrust faults of the Klamath Mountains have been explored by Davis (1969). He proposed that these broadly coeval fault systems are linked structurally, and that the thrust faults of the Klamaths must steepen southward into apparently deeper structural levels now exposed in the western Sierra Nevada. The probable right-lateral offset of the "Calaveras Formation" across the Melones fault (Fig. 3-3) and Saleeby's analysis of right slip along the Kings-Kaweah suture indicate that intraplate thrust faulting in the Sierran-Klamath Jurassic arc had a major strike-slip component.

In conclusion, we find no compelling reason to believe that more than one Early (?) to Late Jurassic magmatic arc is represented in the geologic terrane east of the Great Valley of California. The extreme narrowness of separate exotic island and remnant arcs presumed by others to occur in the western Sierra Nevada and western Klamath Mountains can be explained as the consequence of internal imbrication of a single Jurassic arc in response to oblique Pacific-North American plate convergence. The trench and east-dipping subduction zone responsible for arc magmatism lay to the west, but it is doubtful that either has been preserved in the geologic record.