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A PLATE-TECTONIC MODEL FOR LATE JURASSIC OPHIOLITE GENESIS, NEVADAN OROGENY AND FOREARC INITIATION, NORTHERN CALIFORNIA

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Abstract. Recently published age and structural data allow the reconciliation of previously conflicting models for Late Jurassic genesis of the Josephine, Smartville and Coast Range ophiolites, and the Nevadan orogeny in the Klamath Mountains and Sierra Nevada. The resulting model is consistent with the mode of initiation, location and geometry of the Great Valley forearc basin, and with the lack of a significant forearc basin west of the Klamath Mountains. The Coast Range ophiolite formed by backarc spreading west of an east-facing intraoceanic arc. Soon thereafter, a remnant arc was calved off the west side of this arc, and the Smartville ophiolite formed by backarc (interarc) spreading. During this time, the Sierran phase of the Nevadan orogeny began as the intraoceanic arc encountered the west-facing continental-margin arc of North America. An east-west-trending calcalkaline dike swarm in the Sierra Nevada foothills may mark the trajectory of the colliding arcs at the initiation of the collision. Simultaneously, a new subduction zone was initiated west of the collision (suture) zone, and this new trench propagated southward, thus trapping the Coast Range ophiolite in the new forearc area south of the Klamath area. Intense deformation in the Sierran region resulted from this collision, and both magmatic arcs became inactive as the last remnant of intervening oceanic crust was subducted. Continued westward relative movement of the North American arc was permitted north of the Sierra Nevada owing to the lack of a colliding intraoceanic arc. The result was the westward rifting of the continental-margin arc by intraarc spreading, which formed the Josephine ophiolite in the Klamath area. The Klamath phase of the Nevadan orogeny resulted from contraction of the west-facing intraoceanic arc and Josephine backarc basin beneath the continental margin. Basal sediments of the Great Valley forearc basin were derived primarily from the sutured arc/ophiolite terranes, and were deposited on top of the Coast Range ophiolite, the southern edge of the Klamaths, and the western side of the Sierra Nevada. A new (late Mesozoic) magmatic arc was superposed across the previously accreted terranes, and formed the primary sediment source for the Cretaceous forearc basin.

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INTRODUCTION

The Nevadan orogeny [Knopf, 1929] is one of the most widely recognized deformational events in the Sierra Nevada [Schweickert et al., 1984]. In its type area (Figure 1), it has been modeled as

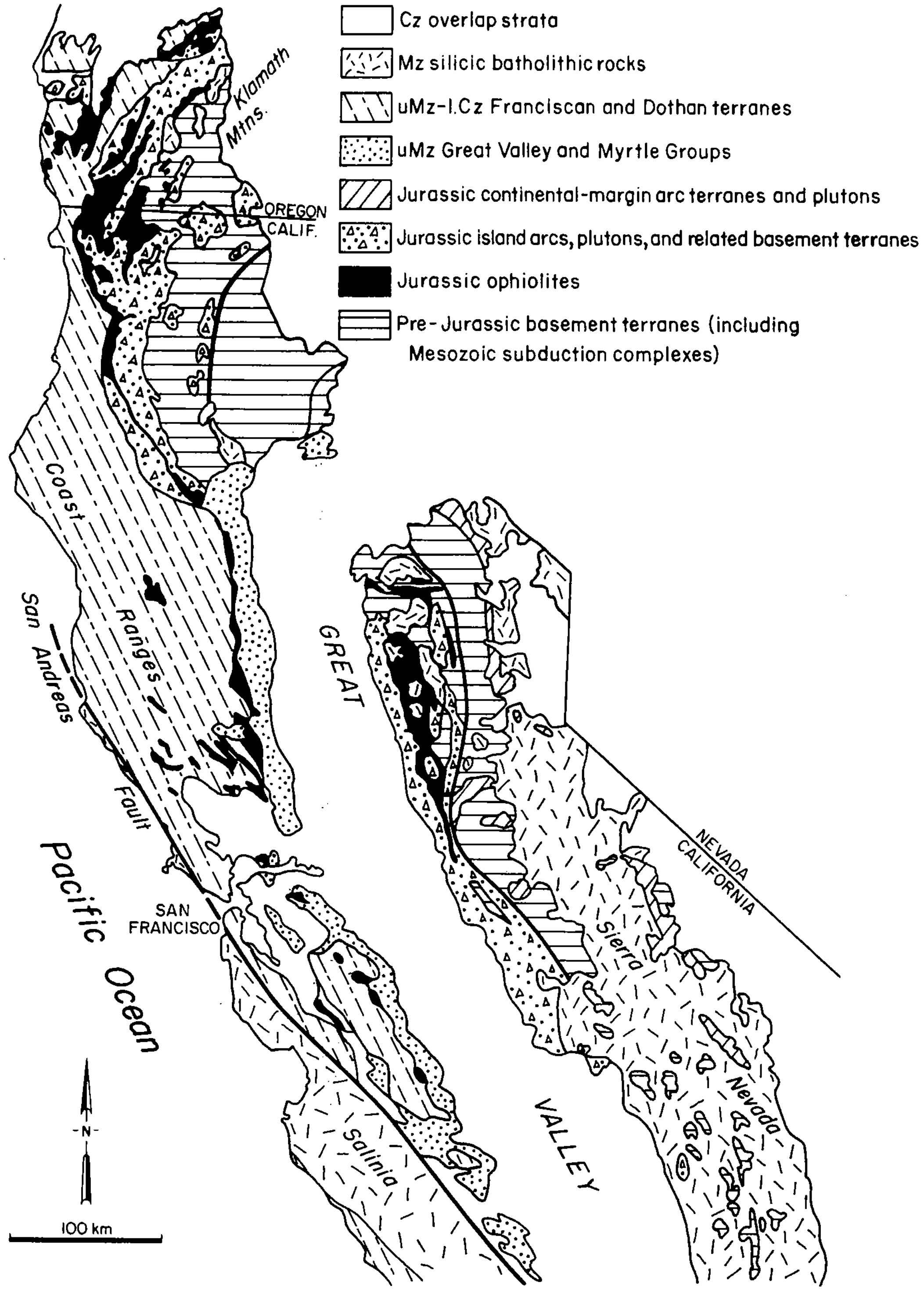

Fig. 1. Generalized tectonostratigraphic map showing location of Jurassic arcs, ophiolites and related terranes, pre-Jurassic basement, Mesozoic batholithic belt, and post-Nevadan sediments and volcanics. This map is highly generalized after Harper et al. [1985].

resulting from arc-arc collision [Moores, 1970; Schweickert, 1978; Schweickert and Cowan, 1975], or oblique rifting and transform processes [e.g., Saleeby, 1981]. We believe that the complex structural relations among the mid- to Late Jurassic magmatic arcs, ophiolites, remnant arcs and sedimentary basins are best explained by a model involving a west-facing continental-margin arc along North America, which collided with an east-facing intraoceanic arc during the Nevadan orogeny [Schweickert and Cowan, 1975]. Immediately preceding this collision, the Coast Range and Smartville ophiolites formed by backarc and/or interarc spreading west of the intraoceanic arc (Figure 2). During and following the Nevadan orogeny, a new subduction zone initiated west of the suture belt, thus trapping the Coast Range ophiolite in a new forearc setting (the Great Valley forearc basin) [Dickinson and Seely, 1979; Ingersoll, 1978, 1982]. Throughout this discussion, "Coast Range ophiolite" refers only to Jurassic oceanic crust east of the San Andreas fault and not part of the Franciscan Complex. Other ophiolitic fragments west of the San Andreas fault and/or part of the Franciscan Complex that have been called "Coast Range ophiolite" do not have as clear paleotectonic affinities as the Coast Range ophiolite exposed along the west side of the Great Valley, in depositional contact with the Great Valley Group.

Models for Late Jurassic orogeny in the Klamath Mountains (also called "Nevadan") differ fundamentally from the above model. The most complete model [Harper and Wright, 1984] involves a mid-Jurassic continental-margin arc (probably a continuation of the Sierra Nevada arc) that experienced intraarc rifting, resulting in formation of the Josephine ophiolite east of a newly formed intraoceanic arc (Figure 2). Soon thereafter, the interarc basin closed and was thrust partially beneath the former continental-margin arc and partially over the coeval intraoceanic arc during the Klamath phase of the Nevadan orogeny [Harper and Wright, 1984]. Eastward subduction seems to have been more or less continuous from the Jurassic to the present in the Klamath area, and no large forearc basin has formed on its west flank, although the Lower Cretaceous part of the Great Valley Group rests depositionally on the southern part of the Klamath Mountains [Ingersoll, 1982].

Regional syntheses of Late Jurassic paleotectonics have been influenced strongly by workers' perceptions of the nature of the "Nevadan" orogeny. The prejudice has been ingrained that the Klamath and Sierran regions record identical forms of Jurassic orogenesis. This stems from the fact that many stratigraphic similarities exist between the two regions. However, close inspection of recent data on timing of events, the positions of the two regions, and the location and geometry of the Great Valley forearc basin indicate significant differences in the kinematic development of the two regions. In addition, two important marine sedimentary units, the Upper Jurassic Galice and Mariposa Formations, have distinctly different paleotectonic settings; the Galice originated as sedimentary fill of an interarc basin [Harper, 1980b, 1984], and the Mariposa formed as trench fill between colliding arcs [Bogen, 1984].

We recognize that the Nevadan orogeny was a complex event and suggest that the two basic models of Harper and Wright [984] for the Klamath region, and Schweickert and Cowan [1975] for the Sierran region may both be useful.

Newly published constraints on ages and structural relations among the ophiolites, arcs, basins and older terranes provide a means of reconciling seemingly conflicting interpretations. In addition, the model proposed below and illustrated in Figure 2 provides an explanation for the presence of the late Mesozoic Great Valley forearc basin and the absence of a comparable basin west of the Klamaths.

TIMING OF EVENTS

Figure 3 summarizes the available evidence on timing of critical events in the northern Coast Ranges, Sierra Nevada and Klamath Mountains. Schweickert et al. [1984] discussed constraints from the Sierra Nevada that date terminal Nevadan deformation and cleavage at 155±3 myBP. Together with Bogen [1984], and Schweickert and Bogen [1983], they noted (p. 978) that the Sierran phase of the Nevadan orogeny probably began earlier, during Mariposa time, as early as Oxfordian. Bogen's [1984] study of the

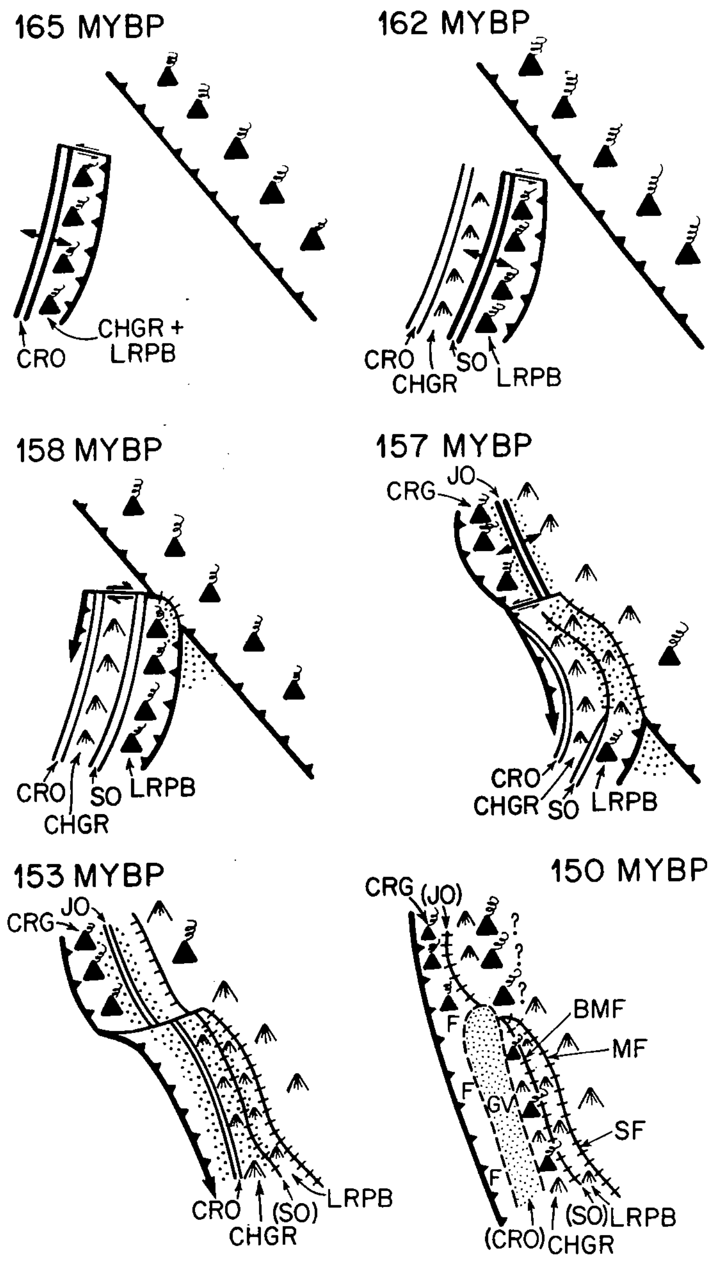

Fig. 2. Sequential paleotectonic diagrams for the Middle to Late Jurassic in northern California. See text for discussion. Active magmatic arcs are shown with smoke, inactive without. Active subduction zones are shown by barbed symbols; suture zones are shown by suture pattern. Rifted continental margin is shown by hachured line. Active spreading centers are shown by divergent arrows on double lines, without implication of exact spreading orientation; inactive spreading centers are shown by double lines without arrows. Transforms are shown by thin arrows. Southward propagating trench is shown by large arrow. Stippled pattern shows sites of deposition of the Mariposa and Galice Formations, and the Great Valley (GV) forearc basin. Abbreviations: CRO, Coast Range ophiolite; SO, Smartville ophiolite; JO, Josephine ophiolite; CRG, Chetco, Rogue, Galice arc complex; F, Franciscan Complex; LRPB, Logtown Ridge arc complex and 200my-old Peñon Blanco arc complex; CHGR, Copper Hill, Gopher Ridge arc complex; BMF, Bear Mountain fault; MF, Melones fault; SF, Sonora fault. (Parentheses around ophiolite names indicate partial preservation within fault zones.)

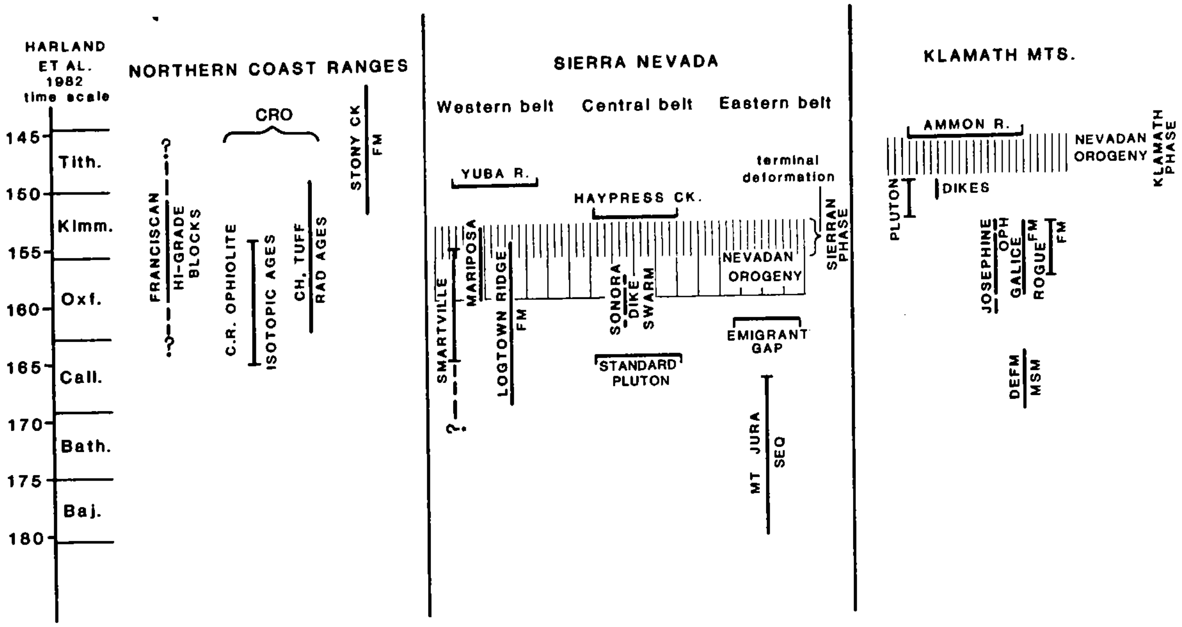

Fig. 3. Age relations of Middle and Late Jurassic stratigraphic units, igneous bodies and deformational events in northern California. Horizontal words are names of dated plutons; horizontal lines give their approximate ages. Vertical names are names of stratigraphic and intrusive units or deformational and metamorphic events ("defm/msm"); vertical bars give approximate age ranges. Dates from the Smartville ophiolite were summarized by Day et al. [1985], and the Emigrant Gap Pluton by Snoke et al. [1982]. Data on the Coast Ranges are from Coleman and Lanphere [1971], Hopson et al. [1981], Ingersoll [1982] and Mattinson [1981]. See text and papers by Harper and Wright [1984] and Schweickert et al. [1984] for other data sources.

Mariposa suggested that it may represent trench fill formed as the underlying intraoceanic arc was being drawn into the North American marginal subduction zone. Thus, the Mariposa was deposited within a remnant ocean basin [e.g., Graham et al., 1975]. Hence, an age range of Oxfordian to middle Kimmeridgian, or approximately 160-152 myBP, is reasonable for the span of the Sierran phase of the Nevadan orogeny, with terminal deformation completed by 155±3 myBP.

For the Klamath region, Harper and Wright [1984] showed that the Nevadan orogeny occurred between 150 and 145 myBP. They cited as critical evidence the 150-my age of dikes and sills that intrude the Galice Formation, and were deformed and metamorphosed together with the Galice. Post-Nevadan plutons, which cut the Galice, have ages of approximately 144 and 147 my [Harper and Wright, 1984; Saleeby et al., 1982; Wright, 1981]. In Harper and Wright's model, the Galice was deposited in a backarc basin before the Klamath phase of the Nevadan orogeny. They commented that the Klamath phase seems to have been slightly younger than the Sierran phase.

Several important generalizations can be made regarding Figure 3:

1. The Sierran phase of the Nevadan orogeny may have significantly predated the Klamath phase of the Nevadan orogeny.

2. The Mariposa and Galice Formations are the same age as chert and tuff that depositionally overlie the Coast Range ophiolite, but the Mariposa is synorogenic with the Sierran phase of the Nevadan orogeny [Bogen, 1984], whereas the Galice is preorogenic with respect to the Klamath phase of the Nevadan orogeny [Harper and Wright, 1984].

3. Although age data are still meager, and full age ranges of the ophiolites are not known, the Coast Range ophiolite may be slightly older than the Smartville and Josephine ophiolites. However, crustal formation in all three was probably concurrent during the Oxfordian to early Kimmeridgian.

4. The Stony Creek Formation, the lowest part of the Great Valley Group, postdates the Sierran phase of the Nevadan

orogeny and is synorogenic with respect to the Klamath phase of the Nevadan orogeny.

STRUCTURAL RELATIONS

The style and vergence of Nevadan deformation differ between the Sierran and Klamath regions. Nevadan structures in the Klamath Mountains appear to be mainly west-vergent low-angle thrust faults and steep slaty cleavages [Davis et al., 1978; Harper and Wright, 1984], although Roure [1983] reported evidence of early east-vergent folds in the Galice Formation.

The Sierra Nevada region shows a more complex structural pattern. In parts of the northern Sierra, earliest Nevadan structures are important west-dipping, east-vergent thrust faults [Day et al., 1985; McMath, 1966; Moores and Day, 1984; Ricci et al., 1985]. Superposed on these structures are steep, west-vergent thrust faults, tight upright folds, and steep slaty cleavage, that form the earliest and dominant main-phase Nevadan structures throughout most of the range [Bogen et al., 1985; Schweickert et al., 1984]. Northeast-trending, late-phase Nevadan folds and cleavages are developed throughout the range, strongly in the north and only moderately in the south.

PROBLEMS OF TRANSLATION AND ROTATION

Several paleomagnetic studies have revealed evidence for large clockwise rotations of parts of the Klamath Mountains block [e.g., Achache et al., 1982; Bogen, 1986; Fagin and Gose, 1983; Mankinen et al., 1984; Schultz, 1983; Schultz and Levi, 1983], but no evidence for significant latitudinal shifts since the Late Jurassic. The sites studied by the above workers all lie within the northern and eastern parts of the Klamath Mountains, northeast of the Salmon tectonic line of Irwin [1985]. This line separates northwest-trending plutonic belts to the south from northeast-trending plutonic belts to the northeast. This suggests that the southwest part of the province may have undergone little or no rotation since the Late Jurassic.

Paleomagnetic studies by Bogen et al. [1985], Frei et al. [1984], and Hannah and Verosub [1980] on metamorphic and plutonic rocks of the Sierra Nevada block show evidence of no significant rotation or latitudinal movement since the Late Jurassic. Therefore, we consider the pre-Cretaceous terranes of the Sierra Nevada and the southern Klamath Mountains to occupy approximately their original (Nevadan) relative positions and orientations.

SEDIMENTARY PROVENANCE

Synorogenic and postorogenic sandstone and conglomerate of the Sierra Nevada, Klamath Mountains and Great Valley forearc basin have similar provenance. The most complete and definitive data come from the Stony Creek and Platina Formations of the Great Valley Group deposited south of the Klamaths and west of the northern Sierra Nevada [Bertucci and Ingersoll, 1983; Ingersoll, 1983]. The provenance of these sediments is a mixture of magmatic-arc, ophiolitic and suture-belt terranes, with increasing proportions of chert-argillite in the north and higher volcanic-lithic proportions to the south [Ingersoll, 1982, 1983]. Most of the detritus at the north end of the basin was eroded from the Klamath coastal promontory formed during the Nevadan orogeny [Ingersoll, 1982, 1983] (Figure 2, 150 MYBP). To the south, a higher proportion of the detritus was derived from the Sierra Nevada. Dickinson et al. [1982], Seiders [1983] and Seiders and Blome [1984] have demonstrated that contemporaneous parts of the Franciscan subduction complex have similar provenance to that of the Great Valley Group, with derivation of northern exposures from the Klamaths and southern exposures from the Sierra Nevada. Most of these Great Valley and Franciscan sandstones and conglomerates are post-Nevadan, although the oldest sediments (Tithonian-Kimmeridgian(?)) overlap in age the Klamath phase of the Nevadan orogeny (Figures 2 and 3). The presence of this suture-derived sediment in the base of the Great Valley Group eliminates the major previous objection to Schweickert and Cowan's [1975] model [Ingersoll, 1983].

Provenance data from synorogenic and preorogenic "flysch" sequences in the Sierra Nevada and Klamath Mountains are fewer and more difficult to interpret; however, they indicate similar mixed provenance of magmatic-arc, ophiolitic and suture-belt terranes [Behrman and Parkison, 1978; Bogen, 1984; Harper, 1980a; Harper and Wright, 1984]. In fact, sandstone compositions of the Kimmeridgian to Neocomian Stony Creek and Platina Formations of the Great Valley Group

[Ingersoll, 1983], the Callovian to Kimmeridgian strata of the central Sierra Nevada foothills (including the Mariposa Formation) [Behrman and Parkison, 1978; Bogen, 1984], and the Oxfordian to Kimmeridgian Galice Formation of the Klamath Mountains [Harper, 1980a; Harper and Wright, 1984] overlap, thus suggesting similar source terranes. Seiders [1983] also has demonstrated that all these units contain distinctive clasts of Triassic radiolarian chert. The model outlined in Figure 2 is consistent with these provenance data.

TECTONIC MODEL

If one accepts the validity of the above interpretations of chronologic, structural and provenance data, then the model shown in Figure 2 reconciles all of the data summarized above, and recent geochemical and petrologic data from the Coast Range ophiolite [e.g., Evarts and Schiffman, 1983; Hopson et al., 1981; Shervais and Kimbrough, 1985]. Schweickert and Cowan's [1975] model is used for the Sierra Nevada, and Harper and Wright's [1984] model is used for the Klamath region.

The azimuth of the pre-Nevadan North American continental-margin arc is shown as 140 degrees, following the trend of pre-Nevadan batholiths [Bateman, 1981]. There are no constraints on the orientation or distance of travel of the intraoceanic east-facing arc, although it is shown with a slight sinistral convergence direction based on Page and Engebretson's [1984] reconstructions.

Ages of the Coast Range and Smartville ophiolites, and their related arcs should overlap, but with general eastward younging due to the nature of backarc (interarc) spreading [Karig, 1971]. The intraoceanic arc (labeled CHGR + LRPB on Figure 2) was active as early as 200 myBP [Saleeby, 1982; Schweickert and Bogen, 1983] and contains clasts of limestone bearing Permian Tethyan fusulinids [Douglass, 1967; Schweickert and Bogen, 1983], so it could have traveled a considerable distance prior to the Nevadan collision. Backarc spreading ceased in the basin of the Coast Range ophiolite as the Nevadan collision began (approximately 160-158 myBP or earlier). East-west-trending andesite, basalt and lamprophyre dikes of the Sonora dike swarm [Schweickert and Bogen, 1983], which have arc affinities [Merguerian, 1986], represent the sigmal-sigma2 plane during the early part of the Sierran phase, and suggest nearly orthogonal convergence during early stages of the collision. Eventually, the arcs in the Sierran region became inactive as southward propagating sutures formed during the closing of remnant ocean basins [e.g., Graham et al., 1975; Schweickert, 1978]. The Mariposa Formation was deposited both within a remnant ocean basin and upon the intraoceanic arc during the collision [Bogen, 1984; Schweickert and Bogen, 1983]. The colliding intraoceanic arc complex acted as an indentor [e.g., Molnar and Tapponnier, 1977; Tapponnier et al., 1982], thus contracting the Sierra Nevada area and allowing the Klamath continental-margin arc to move relatively westward as oceanic crust continued to converge with the Klamath margin. The continental-margin arc in the Klamath area moved westward by intraarc spreading, thus creating the Josephine ophiolite. Parts of the Josephine ophiolite may have formed as early as 164 myBP by intraarc spreading, according to data of Wright and Wyld (in press), although the ophiolitic remnant dated by these workers does not have direct ties to the Josephine ophiolite, and has ambiguous tectonic significance (see Figure 2 for possible complexities along the south side of the Klamaths). The Galice Formation was deposited primarily within the Josephine basin.

Harper et al. [1985] depict east-west ridge segments and north-south transform links in both the Josephine intraarc basin and the Coast Range backarc basin from inferences about dike orientations in the Klamath Mountains and Sierra Nevada. However, there are no rigorous constraints on the original azimuth of transform and spreading segments, and present geometry may result from unknown amounts of rotation during Nevadan thrusting and/or large clockwise post-Nevadan rotations (cited above) in the northern Klamath Mountains. Furthermore, dikes in the western Sierra Nevada are of calc-alkaline-arc affinity, and are not similar to ophiolitic swarms (C. Merguerian and R. Schweickert, unpublished data). Therefore, we have adopted a very simple, diagrammatic spreading geometry for the ophiolite basins in question.

As convergence between North America and the oceanic plate continued, the most likely location for a new subduction zone outboard of the Sierran collision zone would have been along weaknesses in the former backarc area represented by the Coast Range ophiolite [e.g., Casey and Dewey, 1984; Dickinson and Seely, 1979]. As the North American subduction zone was progressively choked by the colliding intraoceanic arc, a natural process would have been the southward propagation of a new trench along weaknesses, such as fracture zones, in the Coast Range ophiolite basin.

The proposed initiation of Franciscan subduction at about the time of the Sierran phase of the Nevadan orogeny may provide an explanation for enigmatic "Nevadan-aged" high-grade blueschist and eclogite blocks in the Franciscan Complex (Figures 2 and 3). The paleogeography depicted for 158 myBP is similar to that postulated by Schweickert [1978], who noted that a modern analog exists in the Philippines-Celebes Sea region. In this area, two opposing arcs are colliding, having been sutured previously in the island of Mindanao [Hamilton, 1979]. Simultaneously with the collision, a new subduction zone has initiated to the east of Mindanao and is propagating southward along with the collision [Hamilton, 1979].

During collision in the Sierran region, continued convergence in the Klamath area led to development of the short-lived Josephine intraarc basin. This basin subsequently closed during the Tithonian as the Klamath arc once again moved as part of the North American plate. By 150 myBP, the late Mesozoic Franciscan - Great Valley - Sierra Nevada continental-margin arc-trench system was developed fully, with magmatism, metamorphism and sedimentation superposed across the previously accreted terranes (Figure 2). This system evolved to its culmination in the Cretaceous [Bateman, 1981; Dickinson and Seely, 1979; Ingersoll, 1979, 1982; Schweickert, 1981].

DISCUSSION

The model presented here is strongly dependent upon the age constraints outlined in Figure 3. As new age data are published, this model will require modification or rejection. A unique aspect of the model is that, while recognizing gross stratigraphic similarities between the Klamath and Sierran regions, it stresses apparent differences between the regions, including timing (Sierran phase versus Klamath phase), tectonic settings of Galice and Mariposa Formations, structural styles of the two regions, and existence of the Jurassic-Cretaceous Great Valley forearc basin west of the Sierra and its absence west of the Klamath region.

Strong points of this model are that, while reconciling different opinions on Klamath and Sierran orogenesis, it successfully explains the location, geometry and mode of initiation of the Great Valley forearc basin, and offers a plausible explanation for "Nevadan-aged" blueschists and eclogites that form enigmatic tectonic blocks within the Franciscan Complex. The model also is consistent with characteristics of modern orogenic belts that show important tectonic contrasts along their lengths. In other words, this is an actualistic plate-tectonic model.

The most vulnerable parts of the model are:

1. The collage of Nevadan and pre-Nevadan terranes may not have developed in their present relative positions. Our model is not dependent on the history of pre-Jurassic terranes in the area. However, Harper et al. [1985] and others have argued for significant lateral motion along the Jurassic continental margin. These motions would complicate, but not necessarily negate, our model. Further paleomagnetic studies and detailed analyses of the kinematic history of Nevadan structures will help test these possibilities.

2. Age constraints we have cited are incomplete and likely will change. More and better age data are needed on the age ranges of the ophiolites, and on crosscutting intrusions in order to bracket ages of deformation. Our model will be invalidated if the Klamath phase of the Nevadan orogeny is shown to be the same age as or older than the Sierran phase.

3. The models of Harper and Wright [1984] and Schweickert and Cowan [1975] call upon the Jurassic intraoceanic arcs to be indigenous and exotic, respectively, with respect to the North American margin. Our integrated model would be refuted if the Galice-Josephine arc-trench system were shown to be exotic, or if the Mariposa-Logtown Ridge arc-trench system were shown to be indigenous. These possibilities will be difficult to prove

or disprove, given the complex nature of the orogen; nonetheless, we encourage other workers to attempt these tests.

We also encourage the development of additional tests of our model.

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