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MIDDLE TO LATE JURASSIC TECTONIC EVOLUTION OF THE KLAMATH MOUNTAINS, CALIFORNIA-OREGON

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Abstract. The geochronology, stratigraphy, and spatial relationships of Middle and Late Jurassic terranes of the Klamath Mountains strongly suggest that they were formed in a single west-facing magmatic arc built upon older accreted terranes. A Middle Jurassic arc complex is represented by the volcanic rocks of the western Hayfork terrane and consanguineous dioritic to peridotitic plutons. New U/Pb zircon dates indicate that the Middle Jurassic plutonic belt was active from 159 to 174 Ma and is much more extensive than previously thought. This plutonic belt became inactive just as the 157 Ma Josephine ophiolite, which lies west and structurally below the Middle Jurassic arc, was generated. Late Jurassic volcanic and plutonic arc rocks (Rogue Formation and Chetco intrusive complex) lie outboard and structurally beneath the Josephine ophiolite; U/Pb and K/Ar age data indicate that this arc complex is coeval with the Josephine ophiolite. Both the Late Jurassic arc complex and the Josephine ophiolite are overlain by the "Galice Formation," a Late Jurassic flysch sequence, and are intruded by 150 Ma dikes and sills. The following tectonic model is presented that accounts for the age and distribution of these terranes: a Middle Jurassic arc built on older accreted terranes undergoes rifting at 160 Ma, resulting in formation of a remnant arc/back-arc basin/island arc triad. This system collapsed during the Late Jurassic Nevadan Orogeny (150 Ma) and was strongly deformed and stacked into a series of east-dipping thrust sheets. Arc magmatism was active both before and after the Nevadan Orogeny, but virtually ceased at 140 Ma.

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INTRODUCTION

Previous models for the Jurassic tectonic evolution of the Klamath Mountains and Sierra Nevada foothills have involved either collision of an exotic arc with North America [Moores, 1970; Schweickert and Cowan, 1975], or the evolution of a single long-lived arc built on the western edge of North America [Davis et al., 1978; Behrman and Parkison, 1978]. Other more complex models have emphasized the role of small plates and transform faulting [Saleeby, 1981, 1983; Harper et al., 1984]. Recently, it has become apparent that much of the North American Cordillera has formed by accretion of numerous terranes, some of which have moved northward by as much as several thousand kilometers [Jones et al., 1977; Davis et al., 1978;

Coney et al., 1980; Saleeby, 1983]. One of the most important questions facing Cordilleran geologists is which terranes are exotic, and which terranes formed along the margin of North America.

In this paper, we present a synthesis of geologic data obtained from several terranes within the Klamath Mountains region (Figure 1), and integrate this information into a tectonic model for Middle to Late Jurassic time. The stratigraphic, geochronologic, and spatial relationships strongly suggest a genetic link between the Middle and Late Jurassic terranes of the Klamath Mountains. We suggest that they formed within a single west-facing magmatic arc, as suggested by previous workers [e.g., Davis et al., 1978]. The purpose of this paper is to document a distinctive pattern in the age and distribution of arc and ophiolite terranes that strongly suggests back-arc spreading occurred at approximately 160 Ma, resulting in the formation of an island arc/back-arc basin/remnant arc triad. The inferred remnant arc (Mid-Jurassic arc terrane) lies east of and structurally above both the Late Jurassic back-arc basin complex (Josephine ophiolite) and Late Jurassic arc complex; this spatial distribution indicates that the arc was west facing. The period of back-arc spreading was followed closely in time by the Nevadan Orogeny (ca. 150 Ma). We feel that these rocks probably formed along the western margin of North America and have undergone a minimum of longitudinal transport. Recent paleomagnetic studies of Paleozoic and Mesozoic rocks of the Klamath Mountains indicate common large-scale clockwise rotations, but no significant latitudinal displacement [Mankinen et al., 1982; Schultz and Levi, 1983; Fagin and Gose, 1983].

We will first present summaries of the stratigraphy, geochronology, and structure of the Jurassic arc and ophiolite terranes of the Klamath Mountains. We will then present the tectonic model.

MID-JURASSIC ARC TERRANE (175-160 Ma)

Volcanic Rocks

Middle Jurassic arc-generated volcanic rocks are presently known to occur within the "western Paleozoic and Triassic subprovince" [Irwin, 1972; Fahan, 1982;

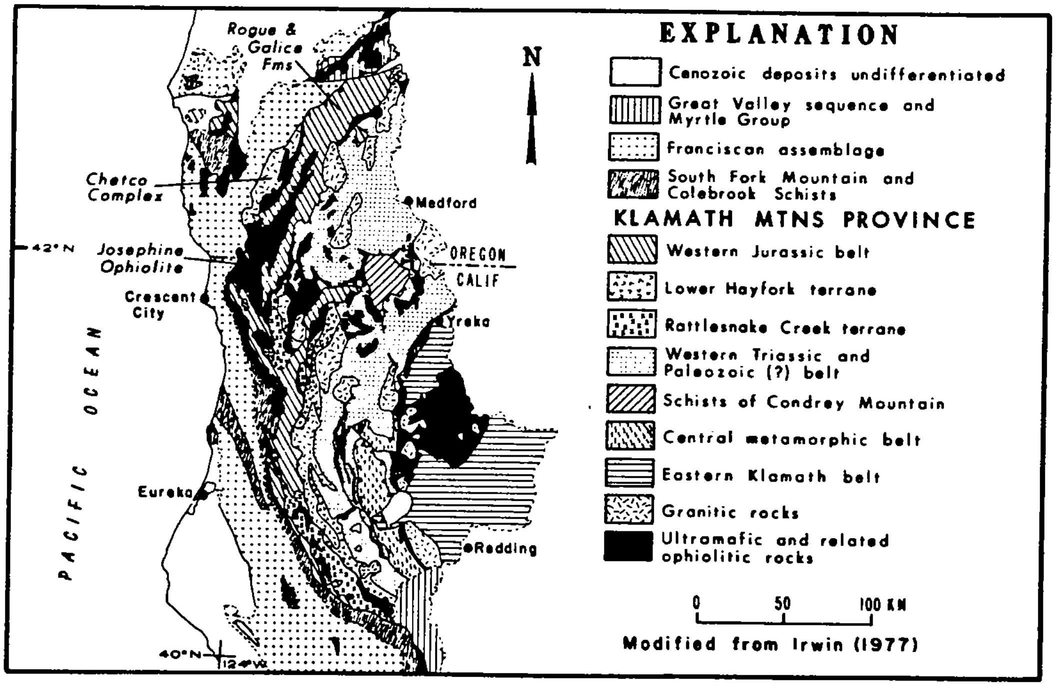

Fig. 1. Generalized geology of the Klamath Mountains. The northern extension of the lower Hayfork terrane is from Donato and others [1982].

Fahan and Wright, 1983] and within the Redding section of the eastern Klamath belt [e.g., Irwin, 1981, Figure 1]. Within the Hayfork terrane of the southwestern Klamath Mountains, a volcanic section up to 6 km in thickness composed predominantly of water-laid volcaniclastic rocks constitutes the lower plate of a regional thrust [Wright, 1981, 1982; Fahan and Wright, 1983]. This group of volcaniclastic rocks (western Hayfork terrane of Wright [1981, 1982]) is in part equivalent to the Hayfork Bally Meta-andesite of Irwin [1972], but see Wright [1982] for a revised structural and stratigraphic interpretation.

The western Hayfork terrane is regionally divisible into two stratigraphic units (Figure 2d). The lower unit is dominated by basaltic to basaltic-andesitic volcaniclastic rocks, including coarse volcanic breccias, lithic tuffs, and crystal-lithic tuffs. Minor lava flows (pillow lava and pillow breccia), argillite and radiolarian chert also occur. The widespread occurrence of graded beds with partial Bouma sequences in the volcaniclastic rocks suggests deposition by turbidity currents. Volcanic clasts consist almost exclusively of porphyritic lava with phenocryst assemblages of either cpx + plag ± ol, or cpx + plag ± hbld. Broken and euhedral crystal fragments of cpx + plag ± hbld are ubiquitous components of the volcaniclastic rocks. Volcanic clasts which lack hornblende are basaltic (49-52 % SiO_2), and those containing hornblende are basaltic-andesitic (52-55 % SiO_2) [Fahan and Wright, 1983]. Three conventional K/Ar ages determined on essentially unaltered brown magmatic hornblende range from 168 to 177 Ma [Fahan, 1982; Fahan and Wright, 1983].

The upper mixed volcaniclastic, epiclastic and hemipelagic unit (Figure 2d) rests with apparent conformity on the underlying, predominantly volcaniclastic unit. Volcaniclastic rocks identical to those of the lower unit are conspicuously abundant, but siliceous argillite, pebble conglomerate and radiolarian chert are also prominent constituents of this unit. Clast types in conglomerates are diverse and include argillite, metachert, limestone, quartzite and granitoid rocks. This unit is significant in that it marks the first appreciable influx of terrigenous epiclastic material into the western Hayfork terrane, indicating that both active volcanic arc and terrigenous source areas were present.

In view of the local occurrence of lava flows and the significant thickness of volcaniclastic rocks containing highly angular volcanic clasts, broken and euhedral crystal fragments, and abundant graded beds with partial Bouma sequences, Wright [1980, 1981] has interpreted the western Hayfork terrane as the deposits of an active oceanic volcanic arc. The occurrence of radiolarian chert indicates

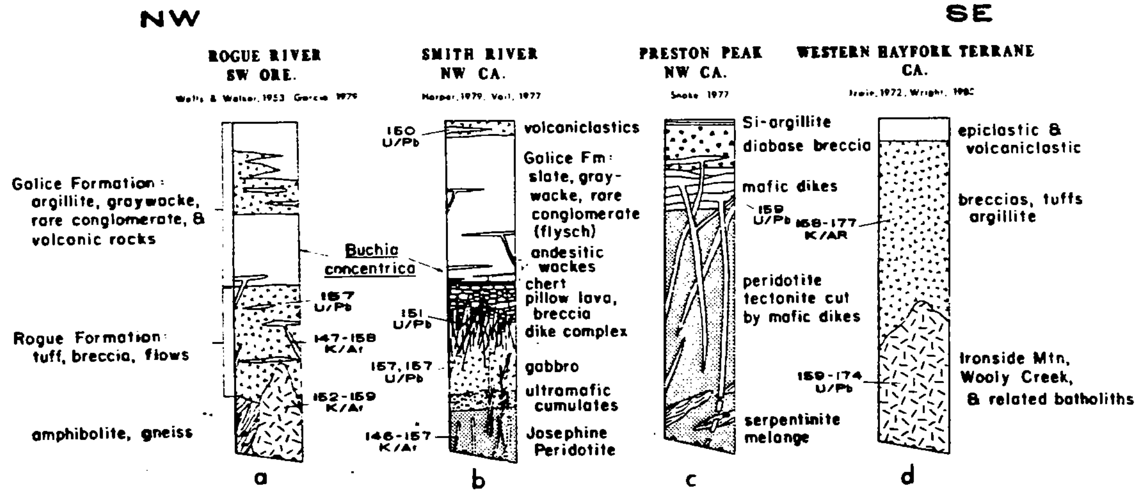

Fig. 2. Summary of the geology and age data for four thrust sheets in the Klamath Mountains.

marine deposition, and the presence of abundant non-volcanic epiclastic detritus in conglomerates demonstrates proximity of the active volcanic arc to an uplifted terrigenous source terrane.

The Redding section of the eastern Klamath belt appears to contain a stratigraphic sequence, with minor unconformities, consisting of volcanic and sedimentary rocks ranging from at least the Devonian to Middle Jurassic (Bajocian; e.g., Irwin [1981]). The Middle Jurassic part of this section is described as containing abundant, largely marine andesitic volcanic rocks including flows, tuffs and breccias [Diller, 1906; Sanborn, 1960]. Although no unequivocal correlation can be made between these rocks and the western Hayfork terrane, one line of evidence does support at least their close proximity in Middle Jurassic time. Limestone clasts collected from the upper unit of the western Hayfork terrane have yielded Late Pennsylvanian and Early Permian gastropods, fusulinids, ostracods and bryozoans [Irwin, 1972]; gastropods from one cobble very closely match the very distinctive Early Permian fauna of the McCloud Limestone of the Redding section that lies stratigraphically beneath the Middle Jurassic volcanic rocks [Irwin, 1972]. This strongly suggests that some of the epiclastic detritus contained within the western Hayfork terrane was locally derived from the McCloud Limestone, thus indicating close proximity of western Hayfork and eastern Klamath volcanism in the Middle Jurassic.

Intrusive Complexes

Wright [1981], Snoke et al. [1982], and Wright and Sharp [1982] have briefly discussed the general distribution, petrologic features, and possible

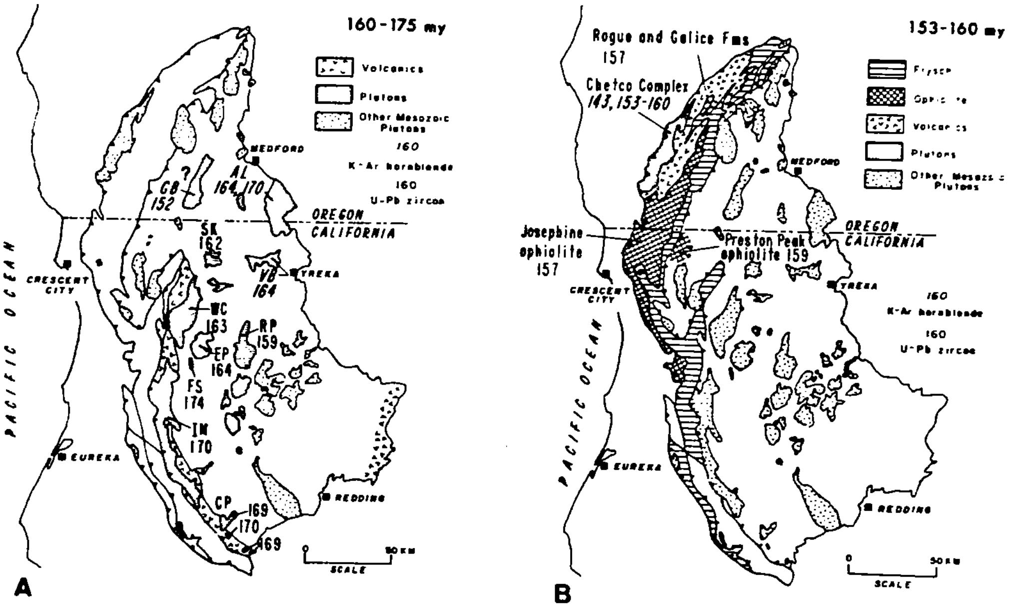

Fig. 3. (a) Distribution and age data for Middle Jurassic or suspected Middle Jurassic plutons and volcanic rocks of the Klamath Mountains. Age data are from Wright [1981], J. E. Wright and W. D. Sharp (manuscript in preparation, 1984), and Allen et al. [1982] for U/Pb ages, and from Lanphere et al. [1968] for K/Ar ages. GB, Grayback; AL, Ashland; SK, Slinkard; VB, Vesa Bluffs; WC, Wooly Creek; IM, Ironside Mountain; EP, English Peak; RP, Russian Peak; FS, Forks of Salmon; CP, Chanchuella Peak. (b) Distribution and radiometric ages for Late Jurassic arc volcanic and plutonic rocks, and ophiolite complexes. K/Ar ages are from Hotz [1971] and Dick [1976], and U/Pb ages on ophiolites are from Saleeby and others [1982]. U/Pb age on the Rogue Formation is from Saleeby [1984].

tectonic significance of a distinctive set of arc-generated intrusive complexes of known or suspected Middle Jurassic age within the Klamath Mountains (Figure 3a) and Sierra Nevada foothills. A detailed analysis of the distribution, geochronology and tectonic significance of these intrusive complexes is in preparation (J. E. Wright and W. Sharp, manuscript in preparation, 1984).

Individual intrusive complexes contain partial to complete lithologic suites composed of the following rock types: (1) olivine- and clinopyroxene-rich ultramafic rocks with relict cumulate features, (2) two-pyroxene bearing gabbroic-to-dioritic rocks that typically evolve into monzodiorites, and (3) intermediate to felsic rocks of similar bulk composition containing hornblende but lacking orthopyroxene. The thick sequence of predominantly volcaniclastic rocks rich in olivine, clinopyroxene and plagioclase phenocrysts and crystal fragments (western Hayfork terrane) is intruded by numerous examples of these intrusive complexes. The intrusive complexes range in age from 159 to 174 Ma (U/Pb ages on zircon; Wright [1981]; Wright and Sharp [1982]; J. E. Wright and W. Sharp, manuscript in preparation, 1984). Wright [1981], Fahan and Wright [1983], and Wright and Sharp [1982] have thus interpreted the volcaniclastic rocks and intrusive complexes as related elements of a Middle Jurassic arc terrane.

The intrusive complexes that roughly parallel the regional trend of their coeval arc-generated volcaniclastic rocks (western Hayfork terrane; Figure 3a) were designated as the Ironside Mountain plutonic belt by Lanphere et al. [1968] and Hotz [1971]. However, recently Wright and Sharp [1982] and J. E. Wright (unpublished data, 1984) have shown that the distinctive suite of Middle Jurassic (159 to 174 Ma) intrusive complexes was emplaced across the diverse pre-Middle Jurassic terranes of the Klamath Mountains including the central metamorphic belt, Stuart Fork terrane, North Fork terrane and eastern Hayfork terrane. Preliminary field observations suggest that this distinctive group of intrusive complexes was also emplaced into the Trinity ophiolite of the eastern Klamath belt (U/Pb geochronology in progress by Wright). It thus appears that the terranes listed above were juxtaposed by about 170 Ma and served as a basement for the Middle Jurassic arc terrane now represented by the volcaniclastic rocks of the western Hayfork terrane and their consanguineous intrusive complexes.

Deformation of the Arc Terrane

Field and geochronological data collectively demonstrate that compressional deformation (thrust faulting and isoclinal folding) and regional metamorphism (greenschist to the almandine zone of the amphibolite facies) occurred at approximately 165-170 Ma [Wright, 1981, 1982; Fahan, 1982; Fahan and Wright, 1983; Barnes, 1983]. This deformational and metamorphic event overlaps in time with arc magmatism, and thus occurred within an intra-arc setting. It is similar in style to the Nevadan Orogeny (discussed below), but is clearly older by at least 15 million years.

PRERIFTING DIKE SWARM (160 Ma)

A mafic dike complex and related diabase breccia of the Preston Peak ophiolite (Figure 2c; Snoke [1977]) structurally overlie the Galice Formation and Josephine ophiolite in extreme northwestern California (Figure 3b). The Preston Peak ophiolite is polygenetic in that the lower ultramafic tectonites have a metamorphic and deformational history predating emplacement of the mafic dikes. The ultramafic rocks vary from massive harzburgite to serpentinite-matrix melange locally containing amphibolite inclusions. Dikes of the mafic complex crosscut the ultramafic and amphibolite tectonites, demonstrating that the upper part of the section was superimposed over an older unroofed ultramafic basement [Snoke, 1977; Saleeby et al., 1982].

An age of approximately 160 Ma has been assigned to the mafic complex of the Preston Peak ophiolite based on a concordant U/Pb zircon age of 159±2 Ma on a late-stage quartz diorite dike within, and probably part of, the mafic complex [Saleeby et al., 1982]. In addition, a retrograded amphibolite of the basement complex yielded a 165±3 Ma K/Ar age on hornblende, interpreted to have been reset during dike emplacement [Saleeby et al., 1982].

The basement complex of the Preston Peak ophiolite, along with structurally overlying metasedimentary and metavolcanic rocks exposed immediately to the south of the mafic complex (Bear Basin road sequence of Snoke [1977]), has recently been interpreted as a northern extension of Irwin's [1972] Rattlesnake Creek terrane [Gray and Petersen, 1982; Norman et al., 1983]. The Rattlesnake Creek terrane is a structurally complex ophiolitic terrane situated between the Galice Formation and the Hayfork terrane (Figure 1; Irwin [1972]).

The mafic complex of the Preston Peak ophiolite has been interpreted as the remains of a primitive, island-arc related tholeiitic assemblage; this suggestion was made on the basis of major element, trace element, rare-earth, and clinopyroxene phase chemistry [Snoke et al., 1977; Snoke and Whitney, 1979]. Although this interpretation does not conflict with the tectonic model for the Klamath Mountains presented below, an alternative interpretation of the mafic complex which is somewhat similar to the "rift-edge facies" of Saleeby et al. [1982] is preferred.

The age and location of the Preston Peak mafic complex suggests that it may have formed during rifting of the Middle to Late Jurassic arc complex. As rifting progressed, a back-arc basin opened and oceanic crust was formed, represented by the 157 Ma Josephine ophiolite. Such pre-rift dike injection and volcanism also occurred prior to the formation of a back-arc basin in southern Chile [De Wit and Stern, 1981]. An alternative possibility is that the dike swarm and breccia formed at the same time as the Josephine ophiolite along the edge of the back-arc basin; this is consistent with the data in that the ages of the dike swarm and Josephine ophiolite are within error limits. The geochemistry of the Preston Peak mafic complex is in fact very similar to that of dikes and lavas of the Josephine ophiolite [Harper et al., 1984].

A mafic dike swarm of the same age as the Preston Peak mafic complex occurs in the western Sierra Nevada [Sharp, 1980]. This dike swarm has been interpreted as representing a manifestation of the same extensional event that resulted in formation of the Late Jurassic Smartville ophiolite [Sharp, 1980; Harper et al., 1984].

LATE JURASSIC ARC AND BACK-ARC BASIN (160-153 Ma)

Josephine Ophiolite and Overlying Flysch

The Josephine ophiolite and overlying flysch ("Galice Formation"; Figures 2b, 3b) comprise a thrust sheet structurally beneath the Preston Peak ophiolite. These rocks were thrust westward over the Rogue and Galice Formations and Chetco intrusive complex during the Late Jurassic Nevadan Orogeny [Dick, 1976, 1977]. This thrust (Madstone thrust) has been mapped by Dick [1976], Ramp [1975], and Smith et al. [1982].

The Josephine ophiolite is a complete ophiolite that includes harzburgite tectonite, ultramafic and mafic cumulates, noncumulate gabbro, sheeted dikes, and pillow lavas (Figure 2b; Harper [1980a]). It is conformably overlain by radiolarian chert which is in turn overlain by, and locally interbedded with, metagraywacke and slate [Harper, 1983]. Locally, however, the ophiolite is directly overlain by a thick olistostrome containing ophiolitic clasts, and is interpreted to represent the sediment fill of a fracture zone [Harper et al., 1983, 1984]. The age of the Josephine ophiolite is well constrained by three U/Pb zircon ages of 157±2, 157±2, and 158±2 Ma on two plagiogranites [Saleeby et al., 1982]. One of the samples (A88z) is a plagiogranite that intrudes the sheeted dike complex, but is also cut by mafic dikes of the ophiolite; thus it is clearly part of the ophiolite. The overlying Galice Formation is well dated by the occurrence of Buchia concentrica (Sowerby), having a known range of Late Oxfordian to Early Kimmeridgian (approximately 160-153 Ma, Harland et al. [1982]), and by the occurrence of Middle or Late Jurassic radiolarians in cherts overlying the ophiolite [Harper, 1983]. Recently, Middle or Late Jurassic radiolarians were separated from cherts interbedded with pillow lavas near the base of the extrusive sequence of the Josephine ophiolite (D. L. Jones, personal commun., 1984).

The metagraywackes and slates overlying the Josephine ophiolite were originally correlated with the Galice Formation by Cater and Wells [1953].

However, the type Galice Formation in southwestern Oregon overlies the Rogue Formation. Nevertheless, the two sequences are very similar in graywacke petrography, and both contain Buchia concentrica [Harper, 1983].

The petrography of metagraywackes and conglomerates indicates a mixed volcanic arc and continental margin source. The continental margin detritus consists primarily of chert and argillite, but includes some metamorphic rock fragments. The common occurrence of chromian spinel also implies ultramafic sources. Detrital glaucophane has also been identified in several graywackes. Chert pebbles from the Galice Formation have yielded Triassic radiolaria [Harper, 1983]. The petrography of the Galice graywackes suggests erosion of older terranes of the Klamath Mountains [Snoke, 1977; Harper, 1980a, 1980b, 1983]. This interpretation is consistent with the available paleocurrent data that indicate sediment transport to the west (i.e., away from the continental margin) [Harper, 1980b]. The Josephine ophiolite and overlying flysch have been interpreted as the basement and sediment fill of a Late Jurassic back-arc (marginal) basin [Vail, 1977; Dick, 1977; Snoke, 1977; Harper, 1980a, 1980b, 1983]. This interpretation is based on the petrography of the graywackes, the close association of the ophiolite with a coeval island arc complex (Rogue Formation and Chetco intrusive complex, Figures 2a, 3b), and the occurrence of 150 Ma (pre-Nevadan) calc-alkaline dikes and sills that intrude the ophiolite and overlying flysch. In addition, the sheeted dikes and pillow lavas have geochemical affinities to island-arc tholeiites [Harper, 1982a, 1984]; this has been attributed to the ophiolite having formed in the earliest stages of back-arc spreading.

The maximum size of the back-arc basin must have been at least as large as the present extent of the ophiolite and overlying flysch; this is approximately 35 km in an east-west direction (allowing for folding), and at least 120 km in a north-south direction. Back-arc spreading was probably only active for approximately 5-7 million years [Harper, 1983], and the spreading was probably slow [Harper, 1984]. The basin was probably more than two kilometers deep based on trace fossils and the lack of calcareous pelagic rocks [Harper, 1982b].

The metasedimentary rocks overlying the ophiolite were strongly deformed and metamorphosed to low grade during the Late Jurassic Nevadan Orogeny. The intensity of deformation increases towards the south, and the grade of metamorphism changes from prehnite-pumpellyite to lower greenschist facies at approximately the latitude of Crescent City, California. Metasedimentary rocks are characterized by isoclinal folds and a weak to strong slaty cleavage, and boudinage of sills is common [Harper, 1980b]. The Josephine ophiolite is essentially undeformed where the metamorphic grade is prehnite-pumpellyite facies, whereas dikes and lavas are foliated where the grade is lower greenschist facies. The Josephine ophiolite and overlying metasedimentary rocks were also folded during a later (Late Cretaceous ?) deformation [Harper, 1980b].

Late Jurassic Island Arc

Structurally beneath the Josephine ophiolite is a complex group of terranes consisting of plutonic rocks of the Chetco complex (Illinois River gabbro), amphibolite-facies basement rocks, older ophiolitic terranes, volcanic rocks of the Rogue Formation, and the Galice Formation (Figure 2a) [Garcia, 1979, 1982; Smith et al., 1982]. These rocks occur entirely within southwestern Oregon, west and north of the Josephine ophiolite, and are bound on the west by a Cretaceous thrust fault (Figures 1, 3b).

The volcanic arc rocks consist predominantly of andesitic pyroclastics and flows of the Rogue; in addition, similar rocks are intercalated and interfinger with metagraywackes and slates of the Galice Formation [Wells and Walker, 1953; Garcia, 1979, 1982]. No fossils have been discovered in the Rogue, but recently a silicic tuff-breccia has been dated at 157±2 Ma and dacite dikes which cut the upper Rogue Formation are 150±2 Ma [Saleeby, 1984]. Thus, the Rogue is equivalent in age to the Josephine ophiolite and appears to represent island arc magmatism active during back-arc spreading. In addition, both the Rogue arc and Josephine ophiolite were cut by dacitic dikes at 150 Ma, during deposition of the Galice flysch.

The type Galice Formation overlies the Rogue Formation and consists of metagraywacke, slate, and rare conglomerate [Diller, 1907; Wells and Walker, 1953]. The Galice Formation is characterized by tight folds and a weakly developed axial planar slaty cleavage, and much of the sequence is overturned in its type area along Graves Creek (G. D. Harper, work in progress, 1984). Bouma sequences are common, indicating deposition by turbidity currents (G. D. Harper, work in progress, 1984). The petrography of the graywackes is very similar to graywackes overlying the Josephine ophiolite, and the two seqences appear to be part of the same clastic wedge that was deposited across the back-arc basin and interfingered with the arc complex (Figure 5b; Harper [1983]).

The plutonic roots of the volcanic arc are represented by the Chetco complex (Figures 2a, 3b; Dick [1976]; Garcia [1982]) and possibly the Rum Creek gabbro [Saleeby, 1984]. The Chetco complex ranges in composition from olivine gabbro to granodiorite, but is predominantly hornblende gabbro [Wells et al., 1949; Hotz, 1971]. Eight K/Ar ages range from 153 to 160 Ma, except for one date of 143 Ma [Hotz, 1971; Dick, 1976; ages have been recalculated using standardized decay constants]. In addition, felsic phases of the Rum Creek gabbro have concordant U/Pb zircon ages of 155±2 and 167±2 Ma [Saleeby, 1984].

The Late Jurassic arc was built on, and intruded into, basement rocks consisting of metaperidotite, metagabbro, amphibolite, and quartz gneiss; these rocks have been called the "Rogue River metaophiolite" by Garcia [1982]. Garcia suggests that these basement rocks may represent oceanic crust upon which the Late Jurassic arc was built. We would like to suggest these metamorphosed and disrupted ophiolitic rocks may be part of the Rattlesnake Creek terrane that was rifted away from the continental margin during back-arc spreading. In addition, Triassic radiolaria have been collected from an ophiolitic terrane beneath the Rogue Formation in southwestern Oregon [Roure and De Wever, 1983], consistent with the age of the Rattlesnake Creek terrane. Roure and De Wever [1983] correlated these ophiolitic rocks with the Josephine ophiolite, but their age and structural position indicate they are older basement rocks beneath the Rogue.

ARC MAGMATISM, 153-150 Ma

It appears as though arc magmatism migrated toward the east just prior to the Nevadan Orogeny. There are two manifestations of this arc magmatism. First, the Bear Mountain plutonic complex was emplaced east of the Josephine ophiolite in at least two distinct pulses at 149 and 153 Ma (Figure 4a; Saleeby et al. [1982]).

Secondly, calc-alkaline dikes and sills were intruded into the Josephine ophiolite and overlying "Galice Formation" (Figure 4a). These dikes are regionally metamorphosed and locally strongly deformed indicating that they are clearly pre-Nevadan in age. U/Pb zircon ages on a dike intruding the ophiolite and a sill intruding volcaniclastic rocks near the top(?) of the "Galice" are 151±2 and 150±2 Ma, respectively [Saleeby et al., 1982]. In addition, Saleeby et al. [1982] report a K/Ar age of 147±6 Ma on a hornblende andesite dike, and Dick [1976] has reported twelve K/Ar dates ranging from 146 to 157 Ma (average 150 Ma) for dikes within the Josephine Peridotite.

ISOTOPIC AGE OF THE NEVADAN OROGENY

The Nevadan Orogeny was originally defined by Blackwelder [1914] as a Jurassic deformational event that affected rocks from western Mexico to Alaska; Blackwelder [1914] noted that the orogeny in California occurred in the Late Jurassic. Most later workers also included metamorphism and plutonism in their definition of the Nevadan Orogeny [e.g., Hinds, 1934; Lanphere et al., 1968]. Lanphere et al. [1968] suggested from their work in the Klamath Mountains that the Nevadan Orogeny spanned the Middle and Late Jurassic, and that the Galice Formation was synorogenic. As noted above, Middle Jurassic and Late Jurassic deformations and associated metamorphism were separated by a period of extensional tectonics. Thus, we will use "Nevadan Orogeny" as redefined by Bateman and Clark [1974] to refer only to the Late Jurassic (pre-Tithonian) period of intense deformation and regional metamorphism. The radiometric dates reviewed in this paper indicate that arc-type magmatism was active before and after the Nevadan Orogeny, at least until 140 Ma; thus, the Nevadan Orogeny apparently did not involve a culmination of plutonism. Our tectonic interpretation of the Nevadan Orogeny is that it was an intra-arc deformation involving the closing of a back-arc basin and resulting in imbrication of the arc, back-arc basin, and remnant arc (Figure 5d).

The isotopic age of regional metamorphism and deformation attributed to the Late Jurassic Nevadan Orogeny is well constrained. An older age bracket is provided by the 150 Ma dikes and sills that intrude the Josephine ophiolite and overlying "Galice Formation" (Figures 2b, 4b) and are metamorphosed and locally strongly deformed. A younger age bracket is provided by post-Nevadan plutons that intrude the Galice Formation; the oldest of these plutons include the Ammon Ridge and Glen Creek complex with U/Pb zircon dates of 147 and 144 Ma, respectively [Wright, 1981; Saleeby et al., 1982]. The Galice Formation is also overlain with great unconformity by Cretaceous strata as old as Valanginian [Dott, 1966]; age of fossils incorrectly reported as Tithonian by Dott (D. L. Jones, personal communication, 1979); the Valanginian spans the time range of approximately 138 to 131 Ma [Harland et al., 1982].

There are also metamorphic ages on rocks metamorphosed during the Nevadan Orogeny. Lanphere et al. [1978] report three K/Ar ages on Galice metagraywackes from the southern Klamath Mountains of 148±2, 151±4, and 153±5 Ma. In addition, Dick [1976] suggests that metamorphism during thrusting of the Josephine Peridotite (the basal unit of the ophiolite) over the Rogue Formation and Chetco complex resulted in resetting of K/Ar ages at 147 Ma.

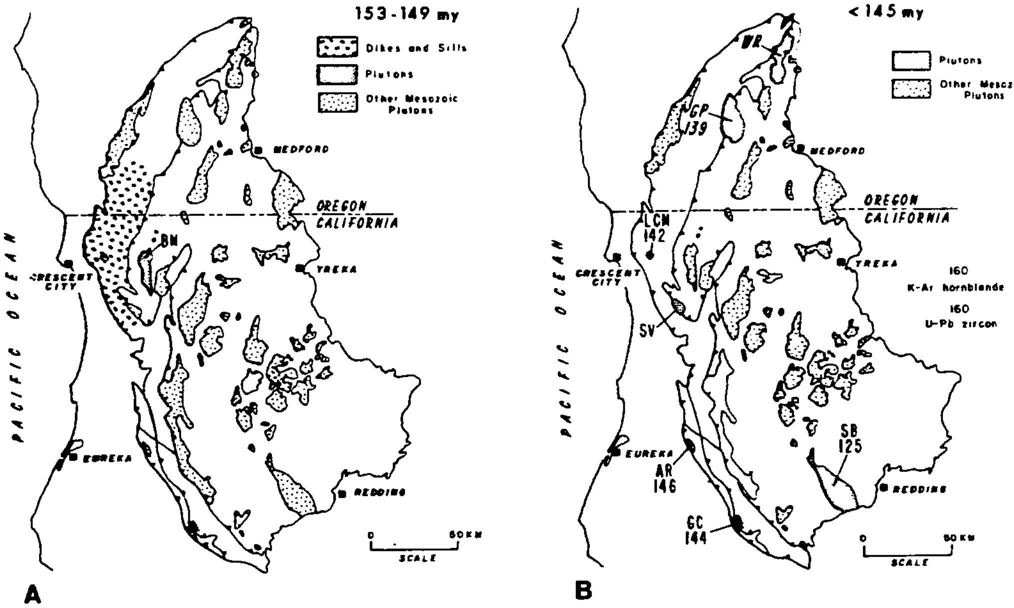

Fig. 4. (a) Distribution and age data for 153-149 Ma arc generated plutons and dikes and sills. The dikes and sills have been dated by Dick ([1976]; K/Ar) and Saleeby et al. ([1982]; U/Pb, K/Ar), and the Bear Mountain plutonic complex (BM) has been dated by Saleeby et al. ([1982]; U/Pb). (b) Post-Nevadan plutons in the Klamath Mountains. WR, White Rock; GP, Grants Pass; LCM, Lower Coon Mountain; SV, Summit Valley; AR, Ammon Ridge; GC, Glen Creek; SB, Shast Bally. U/Pb data are from Saleeby et al. [1982] for LCM, Wright [1981] for GC, and J. E. Wright and W. D. Sharp (manuscript in preparation, 1984) for GC and SB. K/Ar age for GP is from Hotz [1971] and has been recently confirmed by a U/Pb age [Saleeby, 1984].

Thus, the available age data indicate that the Nevadan Orogeny occurred in the time range of 145 to 150 Ma (Late Kimmeridgian or Tithonian). Interestingly, the isotopic age of the Nevadan Orogeny appears to be slightly older in the Sierra Nevada (158-153 Ma, Schweickert et al. [1983]).

POST-NEVADAN ARC MAGMATISM

Numerous post-Nevadan plutons intrude the Late Jurassic arc and ophiolite assemblages in the western Klamath Mountains (Figure 4b). As noted above, some of these plutons are as old as 147 Ma. Although a belt of apparently Early Cretaceous plutons was also defined by Lanphere et al. [1968] in the eastern Klamath Mountains, these plutons are probably Middle Jurassic in age as discussed above (with the exception of the 125 Ma Shasta Bally batholith). It appears from the available age data [Lanphere et al., 1968; Hotz, 1971; Saleeby et al., 1982; Wright, 1981; Saleeby, 1984] that arc magmatism virtually ceased in the Klamath Mountains at approximately 140 Ma, although more U/Pb dates are needed to document this.

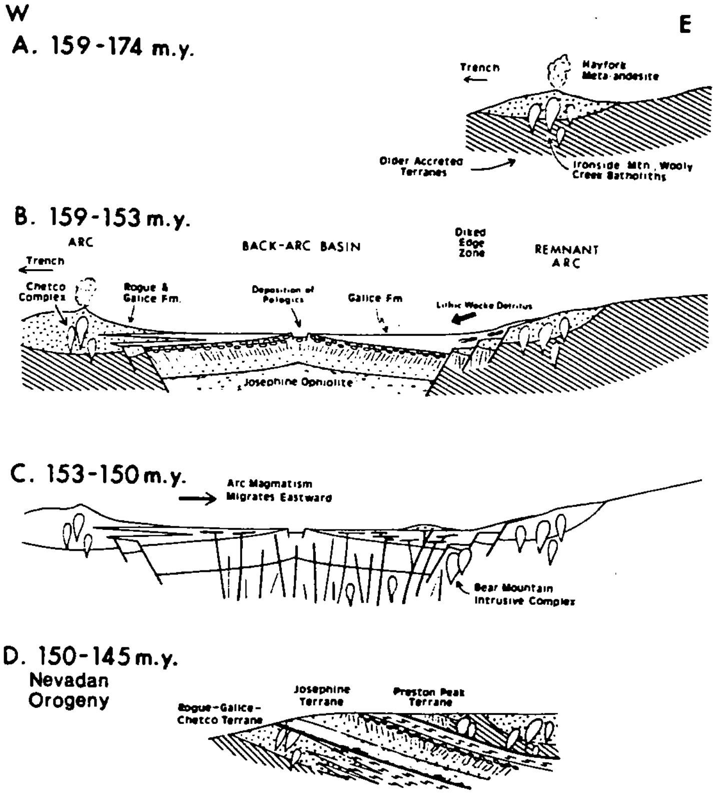

Fig. 5. Proposed tectonic model for the Middle to Late Jurassic tectonic evolution of the Klamath Mountains. (a) Magmatic arc is built on older accreted terranes of the Klamath Mountains in response to eastward subduction. A major deformation and regional metamorphism affected the arc at 165-170 Ma. (b) At approximately 160 Ma, the arc migrates westward relative to North America, resulting in formation of a small back-arc basin and a remnant arc. (c) At approximately 153 Ma arc magmatism migrates eastward, just prior to the Nevadan Orogeny. This results in emplacement of numerous calc-alkaline dikes and sills in the back-arc basin, and emplacement of the Bear Mountain intrusive complex east of the basin. (d) Basin closure and imbrication of arc, back-arc basin, and remnant arc during the Late Jurassic Nevadan Orogeny. Arc magmatism continued until at least 140 Ma.

TECTONIC MODEL

A model for the Middle to Late Jurassic tectonic evolution of the Klamath Mountains is shown in Figure 5. A Middle Jurassic arc represented by the western Hayfork terrane and related plutons was built across and intruded into older accreted terranes of the Klamath Mountains (Figure 5a). Deformation and regional metamorphism affected the western Klamath Mountains at approximately 165-170 Ma [Fahan and Wright, 1983]. This arc complex became inactive by 160 Ma, thus becoming a remnant arc as magmatism shifted westward.

At about 160 Ma, the Middle Jurassic arc complex experienced strong extensional tectonics, resulting in emplacement of the Preston Peak mafic dike swarm and related breccias. Continued extension resulted in opening of a narrow back-arc basin, forming the 157 Ma Josephine ophiolite (Figure 5b). The active arc, represented by the Late Jurassic Rogue Formation and Chetco intrusive complex, migrated westward away from the remnant arc. A submarine fan, derived from erosion of the remnant arc and its basement rocks, prograded across the basin and onto the flanks of the active arc (Figure 5b), resulting in deposition of the "Galice Formation."

Arc magmatism migrated eastward at approximately 153 Ma, resulting in the widespread emplacement of calc-alkaline dikes and sills in the Josephine ophiolite and overlying Galice Formation, and intrusion of the Bear Mountain plutonic complex east of the back-arc basin (Figure 5c).

How?

At approximately 150 to 145 Ma (Nevadan Orogeny), the arc, back-arc basin, and remnant arc collapsed into a series of east-dipping thrust sheets (Figure 5d); intense deformation and regional metamorphism accompanied thrusting. Arc magmatism continued in the western Klamath Mountains until 140 Ma.

We would like to emphasize that this model explains several features of Klamath Mountains geology:

1. The cessation of volcanism and plutonism in the Hayfork terrane at approximately 160 Ma, just as the Josephine ophiolite and Rogue-Chetco arc complex were formed;

2. The stacking of east-dipping thrust sheets, with the back-arc basin complex (Josephine ophiolite and overlying flysch) sandwiched between a structurally lower Late Jurassic arc complex, and a structurally higher Middle Jurassic arc complex;

3. The petrography of western Hayfork and Galice Formation graywackes and conglomerates indicating a mixed continental margin and magmatic arc provenance;

4. The occurrence of arc plutonism both before and after the Nevadan Orogeny. It is also interesting to note that the Klamath Mountains underwent compressional deformations at about 165 and 150 Ma, separated by a period of strongly extensional tectonics at 150 to 160 Ma.

This two-dimensional model explains well the age and distribution of volcanic and plutonic arc rocks and ophiolites in the Klamath Mountains (Figures 3 and 4). We have not addressed the type of back-arc spreading responsible for generating the Josephine ophiolite; i.e., was it "normal" orthogonal spreading with the spreading ridges parallel to the trend of the arc [Karig, 1974], or were short spreading segments separated by long transform faults parallel to the arc as suggested by Saleeby [1981]? The orientations of sheeted dikes (east-west) and fossil transforms (north-south) in the Josephine ophiolite suggests the latter [Harper et al., 1984].

We feel that the Klamath Mountains contains one of the best documented examples of an island arc/back-arc basin/remnant arc system in the geologic record. The preservation of this triad allows a straight forward determination of the direction of subduction as the remnant arc complex lies inboard of the back-arc basin and island arc complexes. Whether this arc system developed along the western edge of North America near its present location has not been demonstrated. However, recent paleomagnetic data from Paleozoic through Jurassic rocks of the eastern Klamath Mountains and from Jurassic plutons in the western Klamath Mountains do not indicate any significant latitudinal displacement relative to stable North America [Mankinen et al., 1982; Fagin and Gose, 1983; Schultz and Levi, 1983].

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