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Geometry and Tectonic Setting of Sea-Floor Spreading for the Josephine Ophiolite, and Implications for Jurassic Accretionary Events along the California Margin

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Ophiolites with Jurassic petrogenetic ages occur in the western Sierra Nevada and Klamath Mountains, California Coast Ranges, and probably underlie much of the California Great Valley. The Josephine ophiolite of the western Klamath Mountains represents one of the most complete, intact, and best studied of the Jurassic ophiolites. A fracture zone history of the ophiolite is indicated by a thin crustal section, highly fractionated ferrobasalts, and a distinctive olistostrome locally overlying the ophiolite interpreted as the sediment fill of a fracture zone valley. Orientations of sheeted dikes, transform remnants, and upper mantle flow fabrics all indicate a sea-floor spreading direction and transform motion parallel to the continental margin. Likewise, some dike orientations and fracture zone features of the Sierra Nevada and Coast Range ophiolites suggest spreading and transform motion parallel to the continental margin. The Great Valley is a major morphotectonic feature that may have originated as a large transform valley that in later Cretaceous time became a forearc basin. Geophysical lineaments of the Valley along with fracture zone features of the northern Coast Range ophiolite and southern Sierra Nevada suggest a left-stepping family of fracture zones in and around the margin of the Great Valley. It is suggested that Jurassic ophiolites of California record major sinistral-sense transform motion and related oblique spreading oriented parallel to the continental margin. Such motion may be linked to the Mojave-Sonora megashear and reflects decoupling between North American and Pacific basin plates during rapid northwestward motion of the North American plate.

INTRODUCTION

Ophiolites with igneous ages clustering around 160 m.y. are one of the most striking features of California geology. These include the Josephine ophiolite in northwestern California, the Smartville ophiolite in the Sierra Nevada foothills, and the Coast Range ophiolite exposed primarily along the western edge of the California Great Valley. Many workers have suggested a marginal basin origin for these ophiolites based on the widespread occurrence of coeval arc volcanic and plutonic complexes in California and southwestern Oregon (Fig. 1) and the occurrence of arc-derived detritus in sediments overlying the ophiolites (Evarts, 1977; Xenophontos and Bond, 1978; Harper, 1980; Saleeby et al, 1982). The Josephine ophiolite represents one of the most intact and best studied ophiolites in the North American Cordillera (Dick, 1976, 1977; Harper, 1980; Saleeby et al, 1982). Geochemical data and stratigraphic relations support its origin in a marginal basin adjacent to an active island arc. Geometric relations in the orientations of sheeted dikes, fracture zone remnants, and mantle flow fabrics consistently indicate a spreading direction parallel to the trend of the continental margin (approximately north-south). The 160 m.y. sea-floor spreading ages that are so widespread in California

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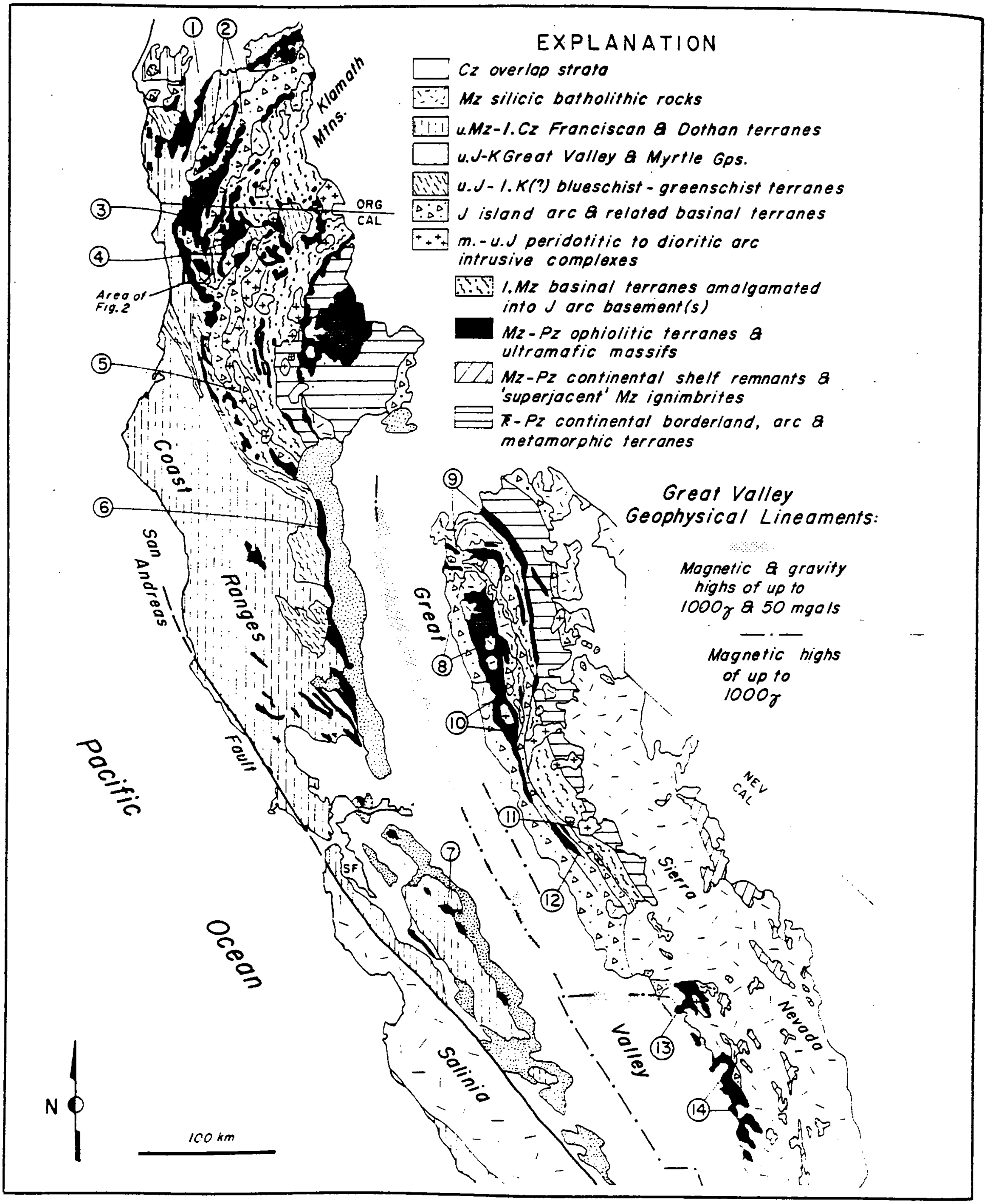

Figure 1—Generalized map showing distribution of ophiolitic, Mesozoic island arc, and related terranes of central California to southwestern Oregon region (modified from Irwin, 1979, and references given in Table 1). Great Valley gravity-magnetic lineaments are from synthesis presented in Cady (1975). Numbers on map refer to locations of successions depicted in Figure 3.

correspond in time with major transform motion of the Mojave-Sonora megashear (Silver and Anderson, 1974, 1983) and oblique components in relative motion along the California margin (Gordan et al, 1981; Engebretson, 1982). The possibility of transform faulting along the California margin in conjunction with the spreading generation of marginal basin crust should be considered very closely. Such processes will simultaneously disperse previously accreted terranes, accrete juvenile crust, and produce structural breaks that may nucleate plate convergence upon changes in relative plate motions.

This paper will focus on the following: (1) the spreading geometry and fracture zone history of the Josephine ophiolite; (2) time and space relations between 160 m.y. ophiolites and Middle-to-Late Jurassic volcanic and plutonic arc rocks of the region between central California and southern Oregon; (3) major Jurassic structural features of northern and central California that suggest or are compatible with transform motion parallel to the margin; and (4) a model for Jurassic transform and spreading geometry and consideration of such a model in the light of regional tectonics and plate kinematic patterns.

Figure 1 is a generalized map of the region from central California to southern Oregon showing major belts of accretionary terranes. Text and diagrams below will focus on the Jurassic ophiolitic terranes, island arc and related basinal terranes, and on Jurassic arc-related plutons. But first, for a regional frame of reference, several other groups of terranes should be noted. These include terranes of the Franciscan and Dothan that were accreted against the Jurassic ophiolitic and arc terranes in mid-Cretaceous to Early Tertiary time and a belt consisting of several Paleozoic terranes in the eastern Klamaths and along the northern and axial Sierra Nevada. In the central and southern axial Sierra, such Paleozoic terranes can be linked genetically to North American sial (Saleeby et al, in press); however, they are likely to have been in a strike-slip dispersal mode throughout much of Mesozoic time. Time relations in the amalgamation of such parautochthonous North America fragments to Paleozoic borderland terranes of the northern Sierra Nevada and eastern Klamaths are poorly understood, although stitching relations by mid-Jurassic peridotitic to dioritic arc plutons provide an important constraint relative to 160 m.y. ophiolites and related arc terranes. Furthermore, a complex sequence of early Mesozoic basinal terranes and related late Paleozoic to early Mesozoic ophiolite fragments formed part of the amalgam that was stitched by the mid-Jurassic plutons. The amalgam of early Mesozoic basinal terranes, Paleozoic borderland, and parautochthonous North American shelf terranes, and the Jurassic arc and ophiolitic terranes were accreted to North America during the Late Jurassic Nevadan orogeny. Cretaceous batholithic rocks form a major stitching belt across the Nevadan orogen. This stitched orogen formed the North American "autochthon" against which Franciscan and Dothan terranes were accreted. Late Jurassic-Early Cretaceous blueschist-greenschist terranes shown on Figure 1 may represent remnants of the Nevadan metamorphic core and perhaps some of the earliest Franciscan-Dothan accretion-related metamorphic events.

Figure 1 also shows the locations of key stratigraphic or structural successions diagnostic of the various Jurassic ophiolitic and arc terranes that are illustrated in Figure 3. Informal names for the successions and references are given in Table 1. The stratigraphic succession at Location 3 is the Josephine ophiolite, which underlies an area of over 800 sq km (309 sq mi) and includes one of the largest ultramafic massifs in the Cordillera. A complete ophiolite sequence is exposed at this location, and much of the ultramafic massif extends into southern Oregon. Attention will focus first on the Josephine ophiolite with emphasis on the geometry and tectonic setting of its sea-floor spreading genesis.

SPREADING GEOMETRY OF THE JOSEPHINE OPHIOLITE

The orientation of sheeted dikes in ophiolites has been used to estimate the trend of the spreading axis (e.g., Pallister, 1981). The strike of the dikes is assumed to have been parallel to the ridge crest; this assumption is supported by the fact that fissures observed at spreading centers are statistically parallel to the spreading axis (Ballard and Van Andel, 1977; Luyendyk and Macdonald, 1977; Van Andel and Ballard, 1979). Several hundred sheeted dikes were measured in the Josephine ophiolite (Harper, 1982) and consistently yield east-west strikes after correction for folding. The dikes dip to the south at 20 to 40° after structural correction; this dip is probably the result of rotations at the spreading center about a subhorizontal axis by listric faulting (Verosub and Moores, 1981; Harper, 1982). Thus, the sheeted dikes suggest that the Josephine ophiolite formed along spreading centers oriented normal to the western Jurassic belt of the Klamaths and presumably the continental margin; i.e., the spreading direction was parallel to the continental margin. The spreading geometry deduced from the sheeted dikes is also substantiated by high-temperature flow fabrics in the peridotite; in general, these fabrics indicate mantle flow in a direction normal to the trend of the sheeted dikes (Harding and Bird, 1983). Such a flow pattern is expected beneath spreading ridges as shallow hot asthosphere ascends and spreads and is supported by seismic anisotropy often observed in modern oceanic upper mantle (Christensen and Salisbury, 1975).

A possible complication in using structural relations within the ophiolite to infer spreading directions is that part of the Klamath Mountains have apparently undergone clockwise rotations of as much as 70° about a vertical axis in Tertiary time (Simpson and Cox, 1980; Fagin and Gose, 1983; Schultz and Levi, 1983). Plutons from the northern part of the range appear to have rotated approximately 75° clockwise, but paleomagnetic data for plutons from the central Klamaths are ambiguous (Schultz and Levi, 1983). Perhaps the best indication of rotations is structural trends in the Galice Formation that lies depositionally on the ophiolite. Galice cleavage and bedding surfaces generally dip steeply to the east and bend from northwest in the southern Klamaths to northeast in the northern Klamaths. If we assume that the change in structural trend is due to the aforementioned rotations, then the northwestern

Klamaths have undergone a large clockwise rotation (as indicated by paleomagnetic data), whereas the central and southwestern Klamaths probably have not rotated appreciably. Such an analysis can be extended into the western Sierra Nevada where paleomagnetic data have shown that units correlative with and having similar structural trends to the Galice Formation of the southwestern Klamaths have undergone little or no rotation (Bogen, 1983; Frei and Cox, 1983). Because the structural trends are north-northwest in the present study area (Loc. 3), a clockwise rotation of up to 20 to 30° is permitted by this line of reasoning. Restoration of such a rotation brings the deduced spreading direction of the Josephine ophiolite into even closer parallelism with the California margin and the major Juassic ophiolite belts located to the south. Such a rotation is used palinspastically in Figure 5, discussed below.

The spreading geometry deduced above is further substantiated by the recognition of a fossil transform valley within the Josephine ophiolite. Transform faults and related fracture zones represent some of the most complex structural features of oceanic domains. The Josephine transform valley is filled with the Lems Ridge olistostrome; this chaotic deposit has not been previously described. Its importance along with the importance of fracture zone features elsewhere in California is one emphasis of this paper, and thus the Lems Ridge olistostrome will be discussed in some depth.

EVIDENCE FOR A FRACTURE ZONE IN THE JOSEPHINE OPHIOLITE

The strongest evidence for a fracture zone in the Josephine ophiolite is the local occurrence of the Lems Ridge olistostrome containing clasts derived from the ophiolite (Harper et al, 1983). The olistostrome has a maximum thickness of approximately 700 m (2,300 ft) and occurs on an east-dipping limb of a large fold where it has been brought to the surface along a reverse fault (Fig. 2). The olistostrome is a complex unit consisting of pebbly mudstone, massive volcaniclastic greenstone, and intercalated graywacke and slaty argillite beds. It is well exposed in road cuts on Lems Ridge and on the South Fork of the Smith River.

The Lems Ridge olistostrome conformably overlies pillow lavas of the Josephine ophiolite, and in one outcrop pebbly mudstone occurs between pillows. The olistostrome is overlain by slates and metagraywackes of the Late Jurassic (Late Oxfordian-Early Kimmeridgian) Galice Formation; the contact is gradational with graywacke and slaty argillite interbedded with volcaniclastic greenstone and pebbly mudstone (Norman, 1984).

Elsewhere, the Josephine ophiolite is conformably overlain by the Galice Formation consisting of a thin pelagic sequence of chert and slaty argillite that is overlain and locally interbedded with graywacke, slate, and minor pebble conglomerate. Graywackes in the basal few hundred meters are characteristically rich in volcanic rock fragments and feldspar, whereas graywackes higher in the section (the bulk of the Galice Formation) are rich in chert and argillite clasts (Harper, 1983). Graywackes within and directly overlying the Lems Ridge olistostrome are petrographically similar to the volcanic-rich graywackes of the lower Galice Formation. This indicates that the Lems Ridge olistostrome is equivalent to the lower Galice Formation and, because of its much greater thickness, suggests that it was deposited in a deep trough.

The most common clast types in the pebbly mudstone are sandstones and shales. The sandstone clasts are diverse and include feldspathic lithic wackes, quartzofeldspathic wackes, and rare orthoquartzite containing a few percent microcline. Other clast types include quartz-mica schist, phyllite, porphyritic andesite, silicic volcanics, pumice, marble, greenstone, metadiabase, metagabbro, chert, and rare ultramafics. Some of the clasts are as much as 15 m (50 ft) in diameter; the larger clasts are mostly metagabbro, greenstone, gray-green chert, and, less commonly, marble.

The volcaniclastic greenstone portions of the Lems Ridge olistostrome include tuffs, volcaniclastic sandstones, and breccias. Where sedimentary textures are not obscured by recrystallization, the clasts can be observed to consist of predominantly volcanic rock fragments (> 85%) and crystals of plagioclase, clinopyroxene, and hornblende. Larger clasts, up to a meter in length, occur sporadically and include argillite, metagabbro, and serpentinite. In addition, large isolated outcrops 15 to 20 m (50–65 ft) long of metagabbro and greenstone occur associated with the volcaniclastic greenstone and are either very large clasts or talus deposits formed on the sea floor. The contact between the volcaniclastic greenstone and pebbly mudstone varies from planar to highly irregular, probably the result of soft sediment deformation.

The volcaniclastic greenstone appears to have been derived from an active volcanic arc. The major and rare-earth chemistry determined for one sample indicates that it is andesitic and light-rare earth enriched, typical of calc-alkaline volcanic rocks (Norman, 1984).

The clasts of ultramafic rocks, metagabbro, metadiabase, and greenstone within the Lems Ridge olistostrome were apparently derived from the Josephine ophiolite. Many of the metagabbro and ultramafic clasts are protomylonites and mylonites. Except for the tectonitic overprint, these rocks are petrographically similar to the rocks from the Josephine ophiolite. The protolith of two ultramafic clasts, determined from the composition of porphyroclasts, is a clinopyroxene cumulate, a common rock type in the Josephine ophiolite. The occurrence of ultramafic rocks indicates that lower crustal portions of the ophiolite were exposed on the sea floor.

One of the strongest lines of evidence that the Josephine ophiolite was the source of many clasts in the Lems Ridge olistostrome is the abundance of pebble- to boulder-size clasts of gray-green chert. Except for their massive nature, the cherts resemble those that overlie the ophiolite elsewhere. Radiolarians separated from several of the chert clasts are Jurassic in age and similar to those from cherts directly overlying pillow lavas of Josephine ophiolite to the north (Jones, 1983, personal communication; Harper et al, 1983).

The Lems Ridge olistostrome is similar to inner fan channel deposits of submarine fans (Walker and Mutti, 1973). However, there are several features of the olisto-

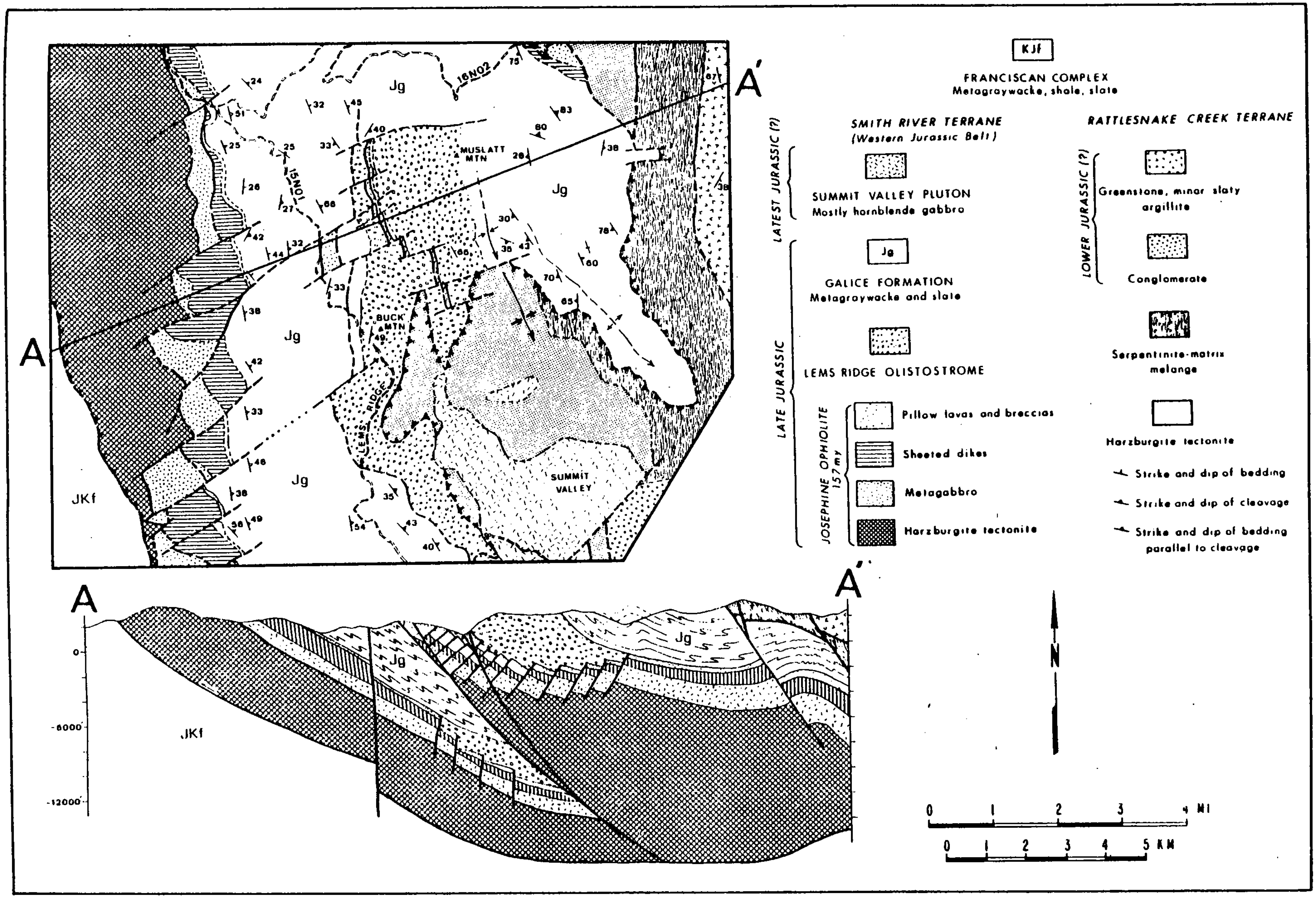

Figure 2—Geologic map of part of the western Klamath belt showing the Lems Ridge olistostrome. Mapping is by G. D. Harper, E. A. Norman, and C. M. Gorman.

strome that suggest it was deposited in a fracture zone valley (i.e., a tectonic depression rather than an erosional valley):

1. Inner fan channel deposits are deposited in channels eroded into slope deposits consisting primarily of mudstone (Walker and Mutti, 1973). In contrast, the Lems Ridge olistostrome directly overlies the Josephine ophiolite.
2. Ophiolite-derived clasts are common, and some are very large. Lower crustal rocks such as metagabbros and serpentinites are commonly dredged from modern fracture zones that offset slow spreading centers (e.g., Bonatti and Honnorez, 1976; Prinz et al, 1976).
3. Many of the ophiolite clasts have cataclastic fabrics, consistent with exposure to the sea floor by faulting.

Modern fracture zones are characterized by deep depressions, the depth of which is dependent on the amount of offset of the spreading centers (Choukroune et al, 1978; Fox et al, 1980). Based on its thickness, the Lems Ridge olistostrome must have filled a depression that was at least 700 m (2,300 ft) deep.

The crustal thickness of the Josephine ophiolite is also suggestive of generation near a fracture zone. Several studies indicate that oceanic crust may be very thin near fracture zones (Fox et al, 1980; Stroup and Fox, 1981; Sinha and Louden, 1983; Corimer et al, 1983). The crustal thinning can be attributed to a decreased magma supply caused by the juxtaposition of relatively cold lithosphere against the spreading center (Nelson, 1981). The crustal thickness near fracture zones may be as little as 1 or 2 km (.6 or 1.2 mi) (Fox et al, 1980; Stroup and Fox, 1981).

The maximum crustal thickness of the Josephine ophiolite, measured from the base of the ultramafic cumulates to the top of the pillow lavas, is only approximately 3.6 km (2.2 mi). In many areas, however, the crustal thickness is only about 1 km (.6 mi) (e.g., Section A–A′, Fig. 2); in these areas, pillow lavas are less than 100 m (330 ft) thick and sheeted dikes may be less than 200 m (650 ft) thick, compared to their maximum thicknesses of 400 and 1,500 m (1,300 and 4,900 ft), respectively.

The crustal thickness of modern backarc basins is variable but is generally between 5 and 8 km (3 and 5 mi) (Ambos and Hussong, 1982), similar to oceanic crust. Thus, the crustal thickness of the Josephine ophiolite is much less than backarc basin or oceanic crust, unless widespread serpentinization of the lower crust is invoked (e.g., Nichols et al, 1980). The very thin crustal section of the Josephine ophiolite, especially west of the Lems Ridge olistostrome (Fig. 2), is possibly the result of generation at a spreading center adjacent to a large fracture zone.

The geochemistry of dikes and lavas of the Josephine ophiolite is also supportive of a fracture zone origin. Lavas dredged near oceanic fracture zones are systematically more differentiated than those erupted along normal ridge segments (Hekinian and Thompson, 1976), especially near the tips of propagating rifts (Sinton et al, 1983). The highly fractionated lavas are ferrobasalts enriched in incompatible elements such as Ti, Zr, and rare earths. This effect is possibly the result of low magma supply rates coupled with moderate cooling rates allowing closed-system fractionation (Sinton et al, 1983). Highly fractionated lavas occur in the upper parts of the Josephine ophiolite. These lavas are ferrobasalts and are strongly enriched in Ti, Zr, and rare earths (e.g., Fig. 4, note Ti-rich samples). The ferrobasalts have up to 13.0 wt % FeO* (total iron as FeO) and 2.4 wt % TiO_2. The geochemistry of lavas directly underlying the Lems Ridge olistostrome is also supportive of a fracture zone origin; dikes and lavas from elsewhere in the Josephine ophiolite are similar to island arc tholeiites but are in some respects transitional to MORB (Fig. 4; Harper, 1984). Pillow lavas from beneath the olistostrome have lower Ti/Cr and higher Ti/V, both of which make them more similar to MORB (Fig. 4); the different chemistry of these lavas might be due to unusual melting conditions in the vicinity of a fracture zone. A second possibility is that the pillow lavas beneath the olistostrome represent more MORB-like lavas on the opposite side of the fracture zone.

The outcrop pattern of the Lems Ridge olistostrome may be used to deduce the orientation of the fracture zone valley and thus the spreading direction. The olistostrome crops out in a north-south belt extending for 13 km (8 mi) (Fig. 2) and must also extend further north in the subsurface as it is downfaulted on its northern end. Note that the olistostrome is absent above the ophiolite both to the west and to the east (Fig. 2); this indicates that the olistostrome filled a north-south depression, suggesting a fracture zone oriented north-south. The fracture zone orientation deduced from the outcrop pattern of the Lems Ridge olistostrome is consistent with the spreading geometry deduced from both sheeted dikes and mantle flow fabrics. This is treated as a strong reference point below in the consideration of regional spreading geometries within other Jurassic ophiolites of California. Attention will now focus on the local tectonic setting of Josephine spreading.

TECTONIC SETTING OF JOSEPHINE SPREADING

Numerous workers have suggested a backarc (marginal) basin origin for the Josephine ophiolite (Dick, 1977; Vail, 1977; Harper, 1980; Saleeby et al, 1982). Several lines of evidence indicate spreading within an island arc setting.

1. The Josephine ophiolite is thrust over a coeval calc-alkaline arc complex comprised of the Rogue Formation and related plutonic rocks (Loc. 2). The Rogue is overlain by the Galice Formation, which is virtually identical in age and petrography to "Galice" that depositionally overlies the Josephine ophiolite (Harper, 1983).
2. Metagraywackes of the Galice Formation overlying the Josephine ophiolite contain abundant andesitic detritus.
3. The Josephine ophiolite and overlying Galice Formation are cut by 150 m.y. calc-alkaline dikes and sills, indicating that arc magmatism occurred within the basin approximately 7 m.y. after formation of the ophiolite.
4. The lavas and dikes have a strong geochemical arc component (Harper, in press). This is indicated by plots using "immobile" trace elements, particularly the Ti/Cr plot (Fig. 4). In some respects, however, the lavas and dikes are transitional between island arc tholeiites (IAT) and mid-ocean ridge basalts (MORB) that are typical of modern backarc basins: (1) the lavas and dikes have Ti/V ratios that mostly fall between 20 and 28, transitional

between IAT and MORB (Fig. 4), and (2) the dikes and lavas have higher Ni contents at a given Ti/Cr ratio than IAT. In addition, Sr and Nd isotopes for a metagabbro indicate derivation from a depleted mantle source characteristic of modern oceanic crust or oceanic island arcs (Shaw and Wasserburg, in press), and the Pb isotopic composition is intermediate between oceanic arcs and MORB (Chen and Shaw, 1982). As noted above, pillow lavas underlying the Lems Ridge olistostrome are much more similar to MORB.

5. The crystallization sequence inferred from the cumulate sequence and from phenocryst assemblages is different from MORB, and the abundance of magnesian orthopyroxene in the cumulate sequence indicates an affinity to island arc magmas (Hawkins and Evans, 1983).

Thus, the regional stratigraphic relations, geochemistry, and petrography all indicate an origin of the Josephine ophiolite within an island arc setting. The unusual transitional chemistry of the dikes and lavas is somewhat problematic in that modern backarc basin basalts are typically similar to MORB (Hawkins, 1977), although transitional basalts have been dredged from the East Scotia Sea (Tarney et al, 1981). The transitional chemistry of Josephine dikes and lavas is considered to be the result of either formation of the ophiolite during the earliest phases of spreading or formation along short spreading segments normal to the trend of the arc as postulated in the model below.

Another manifestation of the 160 m.y. spreading is the Preston Peak dike complex that comprises one of the main components of a polygenetic ophiolitic terrane that structurally overlies the Josephine ophiolite and Galice Formation (Snoke, 1977; Saleeby et al, 1982). The dike complex consists of mafic dikes, sills, and diabase breccia that were built over and intruded into an older ultramafic tectonite and amphibolite basement (Loc. 4). The ultramafic rocks vary from coarsely recrystallized massive peridotite to well-foliated mylonitic rocks. Scattered inclusions of amphibolite are concordantly interlayered with the ultramafic tectonites. These basement rocks are cross-cut by dikes petrographically similar to the overlying dike complex. The basement underwent a severe deformation-metamorphic history and serpentinization prior to injection of mafic dikes and construction of the dike complex.

The dike complex consists primarily of diabase that grades upward into diabase breccia, both of which show a lower greenschist-facies static metamorphism. The intrusive section is approximately 1 to 2 km (.6 to 1.2 mi) thick and consists primarily of dikelike intrusions having chilled margins. The diabase breccia is approximately 500 m (1,640 ft) thick and has been interpreted either as a near-vent pyroclastic deposit (Snoke, 1977) or as a talus deposit formed along a submarine fault scarp (Saleeby et al, 1982). Above the breccia lies a thin sequence of siliceous agrillite.

The Preston Peak complex has been called an ophiolite, but it clearly does not represent oceanic crust generated at a spreading ridge. Based on major, trace, and rare-earth element data (Snoke et al, 1977), as well as clinopyroxene phase chemistry (Snoke and Whitney, 1979), it has been suggested that the ophiolite represents a primitive island arc tholeiite assemblage built across an older unroofed basement. Alternatively, it may be a rift-edge facies formed at the edge of the marginal basin in which the Josephine ophiolite was formed (Saleeby et al, 1982).

The Preston Peak dike complex has been assigned an age of approximately 160 m.y. based on a 159 ± 2 m.y. Pb/U zircon age determined on a late-stage quartz diorite dike and a 165 m.y. reset K-Ar amphibole age on an amphibolite having clear static textural overprinting with retrograde mineral assemblages. The Preston Peak dike complex and Josephine ophiolite are coeval within the analytical error of the dating techniques. This, along with their close spatial relationship, suggests a close genetic link. In addition, new analytical data for the Josephine ophiolite (Harper, 1984) indicate a similar chemistry between the Preston Peak dike complex and dikes and lavas of the Josephine ophiolite. Both the Preston Peak and Josephine samples are peculiar in that they have Cr concentrations lower than MORB, yet have Ni concentrations similar to MORB but higher than arc tholeiites (Fig. 4). Thus, both rock suites are considered to be transitional between MORB and island-arc tholeiites; this distinctive chemistry is considered further evidence for a genetic link between the Josephine and Preston Peak ophiolites.

The Preston Peak ultramafic assemblage has been correlated by Norman et al (1983) with the Late Triassic to Early Jurassic Rattlesnake Creek terrane of Irwin (1972). Such rocks occur along the western margin of the belt of early Mesozoic basinal and ophiolitic terranes that were amalgamated to later become the Jurassic arc basement (Fig. 1). The essential features of this amalgam are its basinal depositional sequences consisting of chert, argillite, flysch, limestone blocks, and pillow lava, and the occurrence of late Paleozoic and early Mesozoic ophiolite fragments (Irwin, 1972; Snoke, 1977; Wright, 1982; Ando et al, 1983).

Structurally overlying the Rattlesnake Creek terrane is the western Hayfork terrane (Loc. 5). The western Hayfork appears to represent the remnants of an island arc volcanic center that is intruded by cosanguinous peridotitic to dioritic plutons (Wright, 1981; Harper and Wright, in press). Interesting time and space relations exist between the western Hayfork terrane, the peridotitic-dioritic arc plutonic belt, and the Josephine ophiolite. Arc volcanism and magmatism ceased in the western Hayfork terrane and in the arc plutonic belt at the time of intrusion of the Preston Peak dike swarm and spreading generation of the Josephine ophiolite (Saleeby et al, 1982; Harper and Wright, in press). Furthermore, the locus of arc volcanism shifted to the Rogue sequence at this time. These relations suggest that Josephine spreading disrupted the locus of Jurassic arc activity in a fashion that is comparable to modern fringing arc systems of the western Pacific where extinct "remnant" arcs are created by rifting and sea-floor spreading resulting in new localization of an active arc segment (Karig, 1972). Such an arc-interarc basin-remnant arc triad is apparent by sequentially viewing sections 2 through 5 in Figure 3. However, the Josephine spreading geometry suggests that the western edge of the Hayfork-Rattlesnake Creek remnant arc was a boundary transform.

Table 1

1. Wild Rogue ophiolite	Ramp and Gray, 1980; Saleeby, in press b
2. Rogue arc complex	Garcia, 1982; Saleeby, in press b
3. Josephine ophiolite	Harper, 1980, 1984; Saleeby et al, 1982
4. Preston Peak dike complex	Snoke, 1977; Saleeby et al, 1982
5. Western Hayfork arc sequence	Wright, 1982; Harper and Wright, in press
6. Northern Coast Range ophiolite	Bailey et al, 1970; Hopson et al, 1981; Blake and Saleeby, unpublished data
7. Southern Coast Range ophiolite	Evarts, 1977; Sharp and Evarts, 1982; Bailey et al, 1970; Hopson et al, 1981
8. Smartville ophiolite	Xenophontos and Bond, 1978; Saleeby and Moores, in press
9. Feather River dike swarm and older ophiolitic slabs	Hietanen, 1981; Saleeby and Moores, in press
10. Folsom dike swarm and Bear Mtns. ophiolitic complex	Clark, 1964; Behrman, 1978; Springer, 1980; Saleeby, 1982
11. Sonora dike swarm and Calaveras complex	Schweickert et al, 1977; Sharp and Saleeby, 1979; Sharp, 1980
12. Penon Blanco arc sequence	Morgan, 1976; Saleeby, 1982
13. Kings River ophiolite	Saleeby, 1978, 1982
14. Kaweah ophiolitic melange	Saleeby, 1979, 1982

Table 1—Informal names and references for stratigraphic and structural successions in ophiolitic and island arc terranes shown in Figure 3.

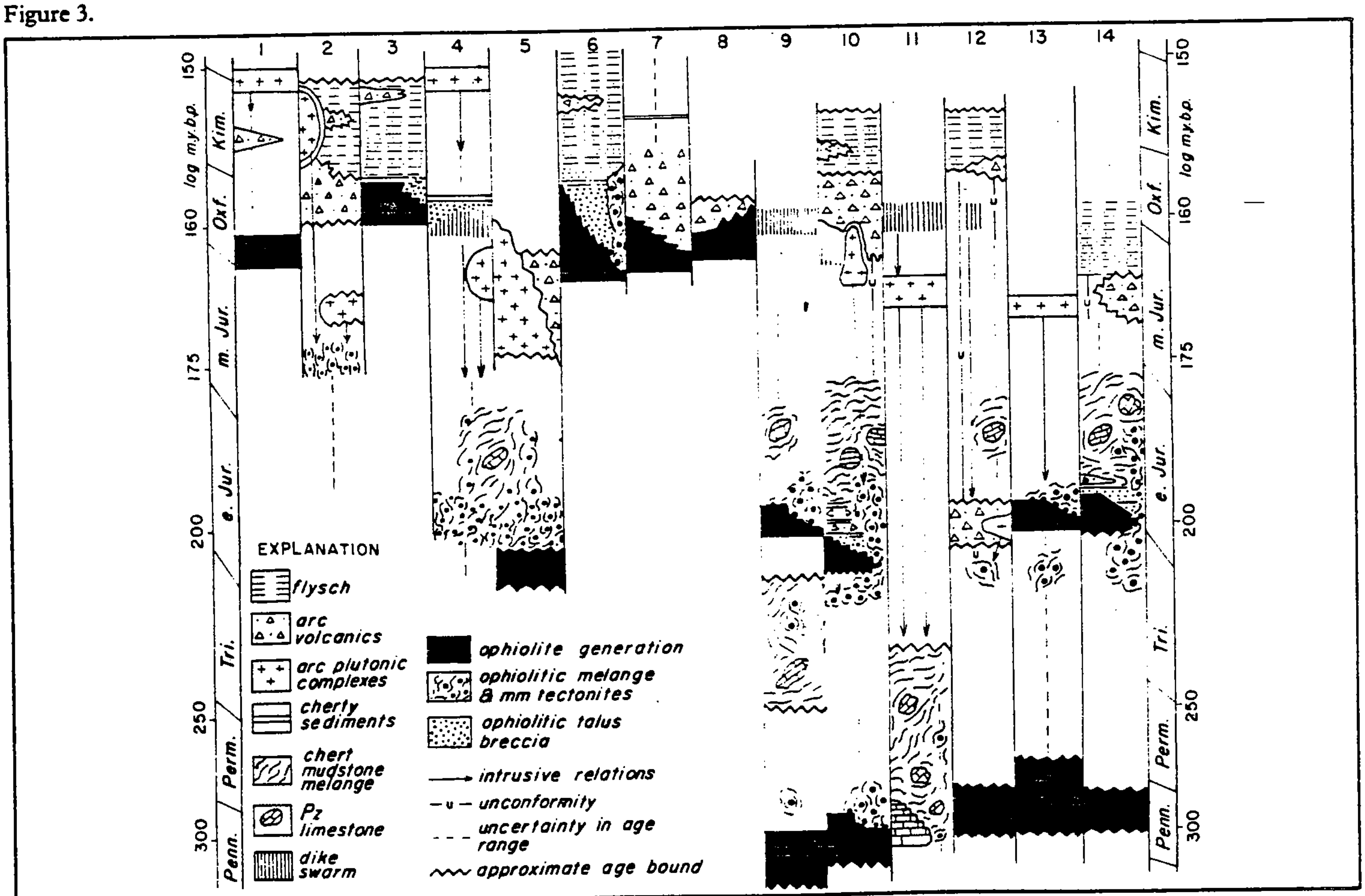

Figure 3—Stratigraphic or structural seccessions diagnostic of ophiolitic and island arc terranes of the western Sierra Nevada, Klamath Mountains, and Coast Ranges. Locations are shown on Figure 1 and references along with informal names are given in Table 1. Log time scale roughly reflects limitations in time resolution because of polymetamorphism and structural disruption, primarily in older assemblages. Rock bodies in a given succession that are not shown in direct contact or connected by unconformity or intrusive symbols are presently in tectonic contact.

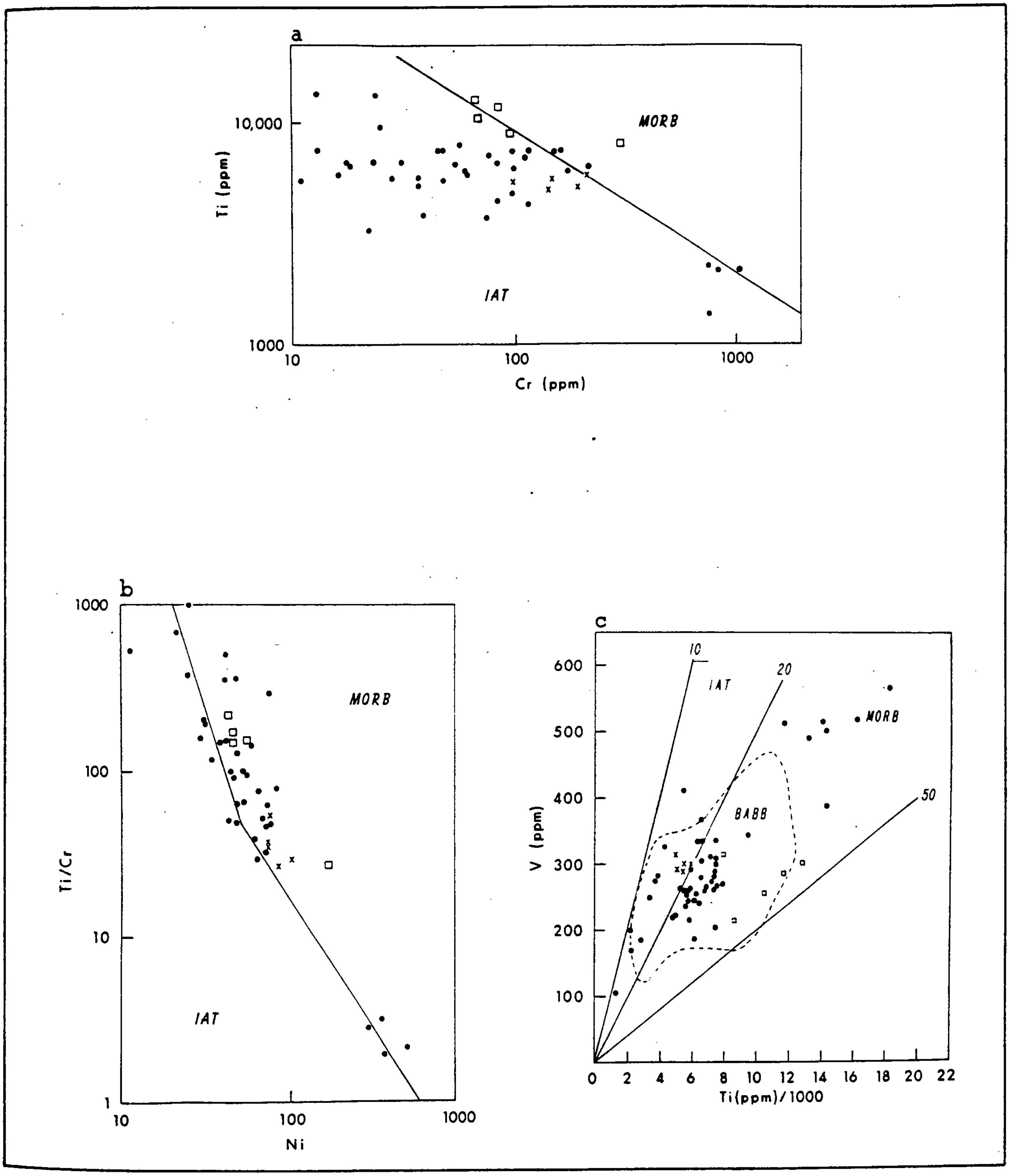

Figure 4—Plots of trace elements for dikes and lavas of the Josephine ophiolite (solid circles). Josephine pillow lavas beneath the Lems Ridge olistostrome (squares), and the mafic complex of the Preston Peak complex (X). Data are from Harper (in press and unpublished data) for the Josephine ophiolite and from Snoke et al (1977) for the Preston Peak complex. (**a**) Ti versus Cr plot after Pearce (1975). (**b**) Ti/Cr versus Ni plot after Beccaluva et al (1979). (**c**) Ti versus V plot after Shervais (1982). MORB = mid-ocean ridge basalt, IAT = island-arc tholeiite, BABB = backarc basin basalt.

The diabase (talus?) breccia of the Preston Peak complex and possibly the structurally complex serpentinite melange of the Rattlesnake Creek terrane (Wright, 1981) may be vestiges of such a boundary structure. Superimposed thrusting has unfortunately obscured possible primary relations.

In summary, the spreading geometry of the Josephine ophiolite, its petrochemistry, and its stratigraphic, temporal, and spatial relations with adjacent arc terranes suggest that its sea-floor spreading generation split a fringing island arc into remnant and active arc segments. Furthermore, spreading and transform trends were parallel to the continental margin. A similar geometry is suggested by structural and spatial relations in the Coast Range ophiolite belt.

FRACTURE ZONE AND ARC SEGMENTS OF THE COAST RANGE OPHIOLITE

The Coast Range ophiolite extends primarily along the eastern margin of the Coast Ranges (Fig. 1) where it forms the basement for the Great Valley Sequence. These rocks lie structurally above terranes of the Franciscan complex along the Cretaceous to Early Tertiary Coast Range thrust (Bailey et al, 1970). Pb/U isotopic ages on the Coast Range ophiolite cluster around 160 m.y. (Hopson et al, 1981). The Coast Range belt consists of two distinctly different segments that are separated by the main drainage system of the Great Valley where it funnels into the San Francisco Bay (Blake and Jones, 1981).

The northern ophiolite segment consists of normal ophiolitic components that were disrupted on the sea floor with the development of major fault scarps that reached deep plutonic levels resulting in talus breccias that became interbedded with ophiolitic pillow lavas (Loc. 6; Hopson et al, 1981; Blake and Saleeby, unpublished data). Blocks of mafic metamorphic tectonite formed contemporaneously with ophiolite melange zones that remained diapirically active through much of Cretaceous time. The northern Coast Range ophiolite has characteristics that are typical of large oceanic fracture zones and is here interpreted as such. The present orientation of the northern Coast Range fracture zone is similar to the transform trend deduced in the Josephine ophiolite. The older (Upper Kimmeridgian) facies of the Great Valley Group interfingers with the ophiolitic talus breccias and is compositionally similar to Galice flysch that overlies the Josephine ophiolite (Harper and Saleeby, unpublished data). Isotopic studies of similar heavy mineral populations are in progress in order to test a possible genetic link between the two flysch sequences. Paleocurrent data suggest that submarine fan channels of the northern Great Valley Sequence followed a north to south orientation along the trend of the Coast Range ophiolite (Ojakangas, 1968). Perhaps the lower intervals of the Great Valley Sequence were funneled along a transform valley system controlled by the northern Coast Range fracture zone.

The southern Coast Range ophiolite segment differs markedly from the northern segment. Here much, and perhaps the entire, igneous sequence represents arc volcanism and plutonism. The arc affinity of the igneous sequence is clearly shown by geochemical data (Bailey and Blake, 1974; Evarts, 1977; Shervais and Kimbrough, 1983; Natland, in press) and is consistent with field observations of abundant silicic and intermediate intrusives and volcanics. The structuring of the arc igneous sequence into an ophiolite stratigraphy suggests an intra-arc rifting environment. The paucity of well-ordered, extensive sheeted dikes indicates a poorly organized rift system. One of the few and best developed sheeted sequences occurs at the northern end of the southern segment where an original east-west orientation is suggested by paleomagnetic data (Williams, 1983); unlike the Josephine ophiolite, however, these dike orientations cannot be interpreted in light of a complete intact ophiolite sequence. The southern Coast Range segment is best displayed in the Diablo Range, and thus this segment will be referred to below as the Diablo rifted arc.

The along-strike spatial relations between the northern Coast Range fracture zone and the Diablo rifted arc mimic the relations between the Josephine ophiolite and the Rogue arc. Such relations suggest longitudinal splitting and transform dispersal of the arc segments by sea-floor spreading parallel to the continental margin. Direct relations between the western Klamath belt and the Coast Range belt cannot be made, although their relative orientations are consistent with one another. The Wild Rogue ophiolite situated west of the western Klamath belt (Loc. 1) also represents a rift basin formed adjacent to an active arc. Perhaps this along with other ophiolite remnants of southwesternmost Oregon are a continuation of the Coast Range belt. The along-strike relations of arc and transform-related ophiolite segments also occur within the Sierra Nevada foothills. However, here a more complex and longer lived interaction of arc and transform tectonics is recorded.

ARC AND FRACTURE ZONE TERRANES OF THE WESTERN SIERRA NEVADA

The western metamorphic belt of the Sierra Nevada consists of interleaved ophiolitic, marine basinal, and island arc terranes that were progressively amalgamated and then finally accreted in Triassic through Late Jurassic time. Most of the pre-Middle Jurassic terranes, together with Paleozoic rocks thought to be parautochthonous to North America, were stitched by Middle Jurassic periodotitic to dioritic arc plutons (Wright and Sharp, 1982; Saleeby et al, in press). Major Late Jurassic faults intervene between some plutons, and thus the details of the stitching pattern are unknown. Ophiolitic terranes of the western Sierra occur in two distinctly different structural and petrogenetic settings.

1. The Smartville ophiolite (Loc. 8) represents an intact 160 m.y. rifted arc sequence (Xenophontos and Bond, 1978) that has been thrust eastward over early Mesozoic basinal and ophiolitic melange terranes (Moores and Day, 1983). A complete ophiolite section is not present, but the outstanding feature is great swarms of 160 m.y. sheeted dikes that both cut and feed into basaltic pillow lavas and basaltic to locally dacitic volcaniclastic rocks. Cumulate rocks are rare, and depleted mantle rocks are not observed.

2. An older, more complex ophiolite belt extends semicontinuously along the entire length of the foothills metamorphic belt. It consists of a polygenetic mixture of ophiolitic melange and ultramafic ± mafic tectonite massifs (Saleeby, 1982) and will be referred to below as the foothills ophiolite belt. Apparent igneous ages within the belt cluster near 300 and 200 m.y., and metamorphic dates on amphibolite-facies tectonites reveal a complex pattern of events with perhaps four distinct metamorphic peaks between 300 m.y. and 155 m.y. dispersed, and in several places superimposed, along the belt (Behrman, 1978a; Saleeby, 1982; Saleeby and Sharp, unpublished data). The 300 m.y. and 200 m.y. protolith assemblages are intermixed and in places cannot even be resolved adequately by Pb/U zircon data owing to polymetamorphism. Initial Pb, Sr, and Nd isotopic compositions are complex and record derivation from multiple mantle reservoirs including ultradepleted oceanic mantle and a distinctly different, possibly subcontinental mantle (Saleeby and Chen, 1978; Saleeby, 1982, and unpublished data; Shaw and Wasserburg, in press). The foothills ophiolite belt constitutes basement for Jurassic arc rocks and is intimately associated with early Mesozoic basinal terranes (Morgan, 1976; Behrman, 1978b; Saleeby, 1979, 1982). Ophiolite exposures in the central foothills (Locs. 10 and 12) are in the cores of large Nevadan anticlines.

Numerous papers have been written on the foothills ophiolite belt from a perspective that it represents a major fracture zone assemblage upon which the Jurassic arc nucleated (Behrman, 1978a; Saleeby, 1978, 1979, 1981, 1982, in press a). Our intention is not to reiterate such discussions here but to draw attention to some of the cogent points.

1. In a number of locations the prevailing Late Jurassic (Nevadan) northwest structural trends of the foothills can be shown to have followed preexisting structures within the ophiolitic basement. These older fracture zone orientations are also parallel to 160 m.y. fracture zone trends of the Coast Ranges and western Klamaths and to major geophysical lineaments of the Great Valley.

2. Mesozoic basinal terranes of the western Sierra occur in exceedingly narrow belts, are in large part olistostromal, and often contain locally derived ophiolitic debris. Such terranes may represent a family of transform valley deposits.

3. The intermixing of 300 and 200 m.y. protolith assemblages appears in part to be primary. The younger assemblage was evidently injected into or along the edge of the older, previously disrupted assemblage, and in places injection occurred in a hot, high-stress environment (Saleeby, 1982). Such tectonic injection probably represents sea-floor spreading adjacent to, or leaking within, a preexisting fracture zone.

4. The foothills ophiolite belt coincides with the locus of a major truncation (or apparent truncation) in the Paleozoic to early Mesozoic North American shelf (Hamilton and Myers, 1967; Saleeby, 1981). Together the ophiolite belt, truncation zone, and fragments of the parautochthonous North America are considered remnants of a major early Mesozoic, and perhaps older, boundary transform between plates of the Pacific basin and the western margin of the North American plate (Saleeby, 1981, in press a). Mesozoic island arc sequences, ignimbrite fields, and batholithic complexes were superimposed across and probably migrated along the boundary zone. This fundamental structure is referred to below as the Sierran boundary transform.

The history of island arc activity in the western Sierra Nevada overlaps with the arc history of the western Klamaths and the southern Coast Ranges. Most notable is the belt of Middle Jurassic peridotitic to dioritic plutons in the Klamaths and Sierras (Fig. 1). The Smartville rifted arc is identical in age to the Diablo rifted arc. Callovian to Lower Kimmeridgian arc volcanics of the western Sierra (Locs. 8, 10, 12, 14) coincide in age with the western Hayfork and Rogue arc sequences of the western Klamaths (Locs. 2, 5). However, basement continuity apparently exists between the Middle and Late Jurassic arc sequences in the western Sierra, whereas the Josephine rift basin intervenes between the Rogue and western Hayfork arcs in the Klamaths. Older, Early Jurassic arc activity is recorded in the central Sierra foothills by the Penon Blanco Formation (Loc. 12, Morgan, 1976; Saleeby, 1982) and in scattered fault-bounded slices in the northern Sierra Nevada (Saleeby and Moores, in press). The older arc-rocks of the western Sierra may have analogs in the Rattlesnake Creek terrane of the western Klamath Mountains (Wright, 1982).

Lower to Middle Jurassic arc sequences rest depositionally on Paleozoic and Triassic basement amalgams of the eastern Klamaths and northern Sierra (Irwin, 1966; McMath, 1966; Clark, 1976). Paleogeographic proximity between these eastern arc sequences and the western Jurassic arc sequences of the Sierra and Klamaths is suggested by two points: (1) Middle Jurassic peridotitic to dioritic plutons appear to stitch basement amalgams of the eastern and western arc sequences (Harper and Wright, in press); and (2) clasts of the distinctive Permian McCloud Limestone occur within Middle Jurassic arc rocks of the western Sierra (Loc. 10; Berman and Parkison, 1978; Saleeby, 1983) and within the Hayfork terrane of the western Klamaths (Harper and Wright, in press). The McCloud Limestone is one of the distinctive formations of the eastern Klamath amalgam. It is not suggested here that the eastern arc sequences are simply continuous lateral equivalents of the western arc sequences. Rather, a complex pattern of transform and oblique rifts is suggested within and along the locus of Jurassic arc activity, and the original spatial relations have been further complicated by the Nevadan orogeny and post-Nevadan dispersion. Attention will now focus on our interpretation of Jurassic sea-floor spreading along the California margin, and how it relates to transform dispersion of arc segments and to plate kinematic patterns.

JURASSIC SEA-FLOOR SPREADING AND TRANSFORM MOTION ALONG THE CALIFORNIA MARGIN

An important finding displayed graphically in Figure 3 is the regional synchronism in ophiolite genesis and basaltic dike intrusion into older accreted terranes at 160 m.y. throughout the region shown in Figure 1. Furthermore, the Sierran-Klamath belt of Middle Jurassic peridotitic to dioritic plutons ceased its main activity at 160 m.y., apparently as a response to the rifting and sea-floor spreading. This reponse is distinctly pre-Nevadan, even though the Nevadan orogeny followed closely in time (ca. 150 m.y.). Parallel relations exist in the southeast California-Sonora, Mexico, region where the continental magmatic arc was disrupted at about 160 m.y. as rapid transform motion of the Sonora-Mojave megashear commenced (Silver and Anderson, 1974, 1983, and personal communication, 1983; Anderson and Schmidt, 1983). Do these parallel events merely reflect a random sampling of events packaged into a mosaic of unrelated terranes? We suggest not and present the following model primarily in hopes of stimulating discussion and future research on processes of transform faulting and ocean crust generation within the Cordilleran orogen.

Figure 5 is a model of the 160 m.y. spreading and transform geometry for the central California to southern Oregon region. The transform geometry of the Josephine ophiolite and the northern Coast Range ophiolite is strongly influential in the model. One of the main interpretations presented regards the structure and origin of the Great Valley basement. Gravity, magnetic, seismic, and basement core data synthesized by Cady (1975) indicate that the Valley is underlain by oceanic-type basement. In Figure 1 the traces of major magnetic and gravity anomalies are shown. Source rock models of the anomalies generated by Suppe (1978) and Griscom (in Saleeby et al, in press) suggest that the linear anomalies arise from steep edges or inflections in gently west-dipping ophiolitic crust. Such crust is disrupted beneath the Coast Ranges and is apparently uplifted and exposed as the Coast Range ophiolite along the Coast Range thrust and younger high-angle faults. The major Great Valley anomalies extend for over 300 km (186 mi) down the axis of the northern and central Valley until a transverse anomaly appears to offset the main anomaly over to the western Sierra foothills (Zietz et al, 1969). South of this transverse anomaly, the main anomalies coincide with the Kings-Kaweah fracture zone assemblage; the last phase of spreading along or within the Kings-Kaweah fracture zone was Early Jurassic (about 200 m.y., Loc. 13, 14).

It is suggested that the origin of the Great Valley geophysical lineaments is revealed by the Kings-Kaweah ophiolite belt, and that these lineaments represent major fracture zones in Jurassic oceanic crust. Two major phases of Jurassic spreading occurred along the Great Valley trend—200 and 160 m.y. The extent of Early Jurassic spreading and transform motion is unknown because of superimposed arc magmatism and dispersal by the 160 m.y. spreading and transform episode. In Figure 5 it is suggested that the transverse lineament between the main mid-Valley and Kings-Kaweah lineaments is the remnant of a short spreading-ridge segment. Repeated dispersal arising from Early Jurassic and/or 160 m.y. spreading along this ridge segment may account for the marked change between the central and southern Sierra metamorphic belt. In the south, very little of the metamorphic belt remains (Fig. 1). To the north, a major Middle to Late Jurassic volcanic arc remains in a deformed but relatively intact state. The paucity of Callovian to Kimmeridgian arc-related strata in the southern foothills suggests major dispersal arising from 160 m.y. spreading. If so, a local boundary between 160 m.y. crust and the older Kings-Kaweah transform lies buried beneath the Valley fill west of the ophiolite belt. Such a boundary could step westward at the transverse lineament and continue northward as the main axial Great Valley lineament. The lower amplitude southern continuation of the axial lineament could be a fracture zone within 160 m.y. crust, akin to the northern Coast Range fracture zone. South of the San Francisco Bay area, the possible continuation of the northern Coast Range transform is shown as a boundary zone against the Diablo rifted arc. This suggests that a normal rift edge between juvenile oceanic crust and the rifted arc lies concealed where the drainage of the Great Valley funnels into the San Francisco Bay area. Dike orientations reflecting this normal rift edge are shown provisionally in Figure 5 after Williams (1983). As noted earlier, an analogous pattern in longitudinal dispersion of arc segments is suggested in the structural and stratigraphic relations between the Josephine ophiolite and the Rogue arc sequence. The Wild Rogue ophiolite (Loc. 1) probably represents yet another remnant of a rift basin formed adjacent to a Late Jurassic arc segment. Dike orientations for this ophiolite are shown tentatively based on the predominance in orientations observed in the Rogue River canyon where the ophiolite belt was first described (Ramp and Gray, 1980) and dated (Saleeby, in press b).

The Great Valley basement is suggested to be primarily the remnants of a composite leaky transform system much like the Cayman Trough (Perfit and Heezen, 1978) or the Andaman Sea (Curray et al, 1979). The Cayman Trough is of particular interest because a small spreading ridge segment has inserted itself and is spreading along the axis of a large preexisting transform deep that has been instrumental in dispersing active and extinct arc segments. An analogous situation is suggested in Figure 5 with the Great Valley rift. Igneous accretion along the Great Valley appears to have nucleated along the preexisting Sierran boundary transform; the eastern oceanic wall of the boundary transform contains fragments of late Paleozoic fracture zone crust against which, and perhaps into which, Early Jurassic ophiolitic crust was generated (Locs. 11, 13, 14). Direct contacts between 160 m.y. ophiolite and this older Sierran fracture zone complex are not observed. This older fracture zone complex constituted much of the Sierran foothills arc basement at 160 m.y. Where 160 m.y. intra-arc rifting occurred within the older fracture zone framework, systems of sheeted and isolated dikes intruded preferentially along the preexisting fracture zone fabric; examples include the Feather River and Folsom dike swarms, which were emplaced into older ophiolitic melange (Locs. 9, 10), and perhaps the Smartville ophiolite (Loc. 8). In contrast, the Sonora dike swarm (Loc. 11) was emplaced into the mid-Jurassic arc plutonic belt and its annealed metamorphic wall rocks (Sharp, 1980); here the dikes trend generally east-northeast, indicating extension parallel to the axis of the Sierra Nevada. These relations suggest that a very limited

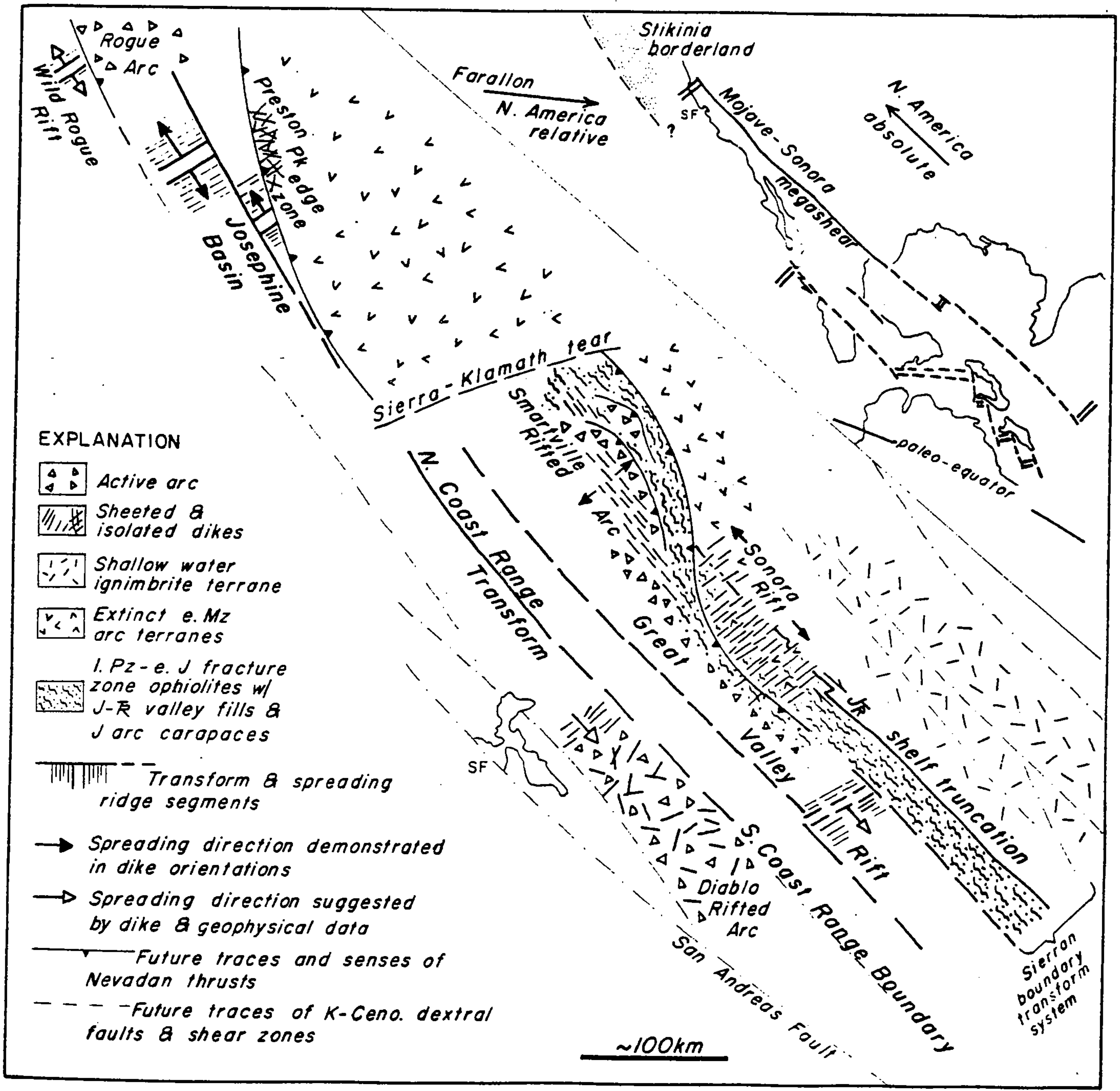

Figure 5—Sketch map showing proposed spreading and transform geometry for 160 m.y. ophiolites of California and southwest Oregon and their spatial relations with coeval and older Mesozoic arc terranes. Also shown are the traces of "future" Late Jurassic thrust faults. Ancillary map in upper right is Mercator projection of Mojave-Sonora megashear (after Anderson and Schmidt, 1983) showing its relation to 160 m.y. rift and transform features of main figure. Stikinia borderland region is taken after Davis et al (1978), Monger and Irving (1980), and Saleeby (1983). Absolute motion of North America is after Gordan et al (1982); relative motion between North America and Farallon plate is after Engebretson (1982).

component of 160 m.y. transform motion occurred along the Sierran foothills, perhaps an amount equivalent to the amount of extension represented in the Sonora dike swarm. As shown in Figure 5, the main transform motion is suggested to have occurred along Great Valley lineaments and the northern Coast Range transform.

Figure 5 also shows the general distribution of the Early to Middle Jurassic arc sequences that were built over the Paleozoic borderland amalgam. As noted above, arc volcanism and plutonism ceased in these regions during or prior to the commencement of the 160 m.y. rift-transform system. In the southeast, an extensive ignimbrite terrane was active over the North American sialic edge during the 160 m.y. rifting event. It should be noted that blocks and clasts of quartzite and silicic tuff occur within the Jurassic chert-argillite-sandstone olistostrome fill of the Kaweah transform valley (Loc. 4). The ignimbrite terrane developed in an environment dominated by shallow-marine deposition. A number of large caldera complexes and major slump and olistostrome complexes have been identified (Fiske and Tobisch, 1978; Saleeby et al, 1978; Busby-Spera, 1983). The ignimbrite terrane apparently formed over the actively fragmenting North American shelf edge.

Figure 5 gives an impression of a left-stepping family of transforms between the Josephine ophiolite, northern Coast Ranges, axial Great Valley and Kings-Kaweah belts (lineaments). The ancillary map in the upper right shows 160 m.y. spreading and transform geometry suggested for the Mojave-Sonora megashear (Silver and Anderson, 1974, 1983, personal communication, 1983; Anderson and Schmidt, 1983). The map is modified from Anderson and Schmidt (1983), who constructed it by a Mercator projection from the pole of rotation defined by the megashear. Temporal and spatial relations and the sinistral sense of movement all suggest a link between the two systems. The Josephine–Great Valley rift system and megashear together define a zone of major decoupling between the North American plate and plates of the Pacific basin. This may be viewed in the context of the late Middle to Late Jurassic rapid northwestward absolute motion of North America suggested by Gordan et al (1981) with a linkage to spreading in the equatorial Atlantic. The model is also consistent with sinistral-sense oblique convergence between North American and the Farallon plates suggested by Engebretson (1982). The decoupling zone disrupted both fringing island arc terranes of central California and southern Oregon and the continental arc terrane of southeastern California and Sonora. The petrotectonic significance of the southern Sierra ignimbrite field is uncertain; it could be a direct response to rifting along the sialic edge, or it could represent a major extensional cycle within the continental arc.

THE NEVADAN OROGENY AND POST-NEVADAN DISPERSION

The Nevadan orogeny was originally defined as a Jurassic deformation event in the Sierra Nevada region by Blackwelder (1914). Numerous workers in subsequent years included batholith emplacement and related metamorphism as part of the Nevadan orogeny, which in effect expanded its time span to include much of the Mesozoic. The Nevadan orogeny was redefined by Bateman and Clark (1974) as a short-lived, intense deformation event in Late Jurassic time. An approximate timing of 150 m.y. fits Bateman and Clark's (1974) definition and time relations in the western Klamaths discussed in Saleeby et al (1982) and is adopted here. The main manifestations of the Nevadan orogeny in the Sierra-Klamath belts are the development of through-going fault systems along the western margins of the ranges and regional folding with the development of slaty cleavages, primarily in argillaceous strata. Nevadan metamorphism is generally lower- to subgreenschist facies. Two notable exceptions are at Location 10 where amphibolite facies conditions were reached because of primary heat within the volcanic arc (Saleeby, 1982) and in a large window (Condrey Mountain) exposing blueschist-greenschist rocks east of Locations 3 and 4 in the Klamath Mountains (Klein, 1977). The Condrey Mountain window is of interest because it exposes possible Josephine basin-affinity rocks that were thrust eastward beneath the extinct mid-Jurassic arc and its basement amalgam. Schists similar to those in the Condrey Mountain window occur in the northern Coast Ranges and, in particular, along the western perimeter of the Klamath province. A fundamental question is whether these schists represent additional thrust sheet(s) of Josephine basin rocks that were extracted from the Nevadan metamorphic core and reshuffled during early Franciscan-Dothan accretion.

Eastward underthrusting of the Josephine basin beneath older terranes of the Klamath Mountains is supported by structural studies (Irwin, 1977; Snoke, 1977; Klein, 1977) and seismic refraction and magnetic data (Fuis et al, in press). This sense of thrusting is depicted on Figure 5 with underthrusting nucleating along the boundary structure between the Josephine basin and the extinct Middle Jurassic arc terrane. The Preston Peak dike complex and perhaps ophiolitic melange of the Rattlesnake Creek terrane represent possible remnants of this boundary zone. The opposite sense of thrusting is depicted in the northwestern Sierra where the Late Jurassic arc terrane and its fracture zone basement are thrust eastward over the extinct mid-Jurassic arc and its basement amalgam (Moores and Day, 1983). To the south the sense of thrusting is irresolvable.

The change in Nevadan vergence from the Klamaths to the northern Sierra suggests a major Nevadan-age tear between the two ranges. Such a tear could have nucleated along a spreading ridge segment similar to that hypothesized for the southern Great Valley transverse lineament. Alternatively, the change in vergence could have been directly influenced by longitudinally propagating rifts in the Smartville rifted arc (including Locs. 8, 9, 10). In this case, buoyant crust consisting of warm attenuated active arc material and bounding and subjacent fracture zone material preferentially moved tectonically over the extinct arc and its Paleozoic borderland amalgam.

The Nevadan orogeny is widely viewed as a collisional orogenic event (Schweickert and Cowan, 1975; Moores and Day, 1983). The questions that must be considered closely are what collided with what, where were they when they collided, and to what extent has post-collision dispersion modified them. These questions must be viewed in a larger context than the area shown in Figure 1. Basement amalgams for the Jurassic arc terranes of the western Sierra-Klamath belt can be compared quite closely to the much larger Stikinian amalgam of British Columbia (Davis et al, 1978; Saleeby, 1983). This large amalgam began to accrete to North America in mid-Jurassic time, probably in California paleolatitudes, and subsequently was dispersed northward in Cretaceous and Tertiary time (Monger and Irving, 1980). It seems likely that the rift geometry depicted in Figure 5 occurred within or near the southern termination of the actively accreting Stikinian amalgam. This amalgam is shown as a Stikinian borderland in the ancillary sketch of Figure 5. Late Jurassic flysch sequences notably enriched in early Mesozoic chert detritus (Loc. 2, 3, 6, 10, 12, 14) are likely to have been derived from Stikinian orogenic highlands. Perhaps there is a general provenance link between the flysch deposits and the initial Late Jurassic molasse of the Bowser Basin that blankets a large portion of Stikinia and is rich in early Mesozoic chert detritus (Eisbacher, 1981). The collapsing Stikinia borderland may have driven short-lived consumption of 160 m.y. rift basin crust and convergence across transform links resulting in what California workers call the Nevadan orogeny.

Modern cases of active spreading and transform faulting within a collapsing arc framework are nicely displayed in the Bismark, Soloman, and Coral Seas of the Melanesian reentrant. Here the collapse is being driven by the impact of the Ontong-Java Plateau on the outer fringes of the system. This brings up another important question concerning the possible impact of the Wrangellian amalgam with the outer fringes of the Stikinian borderland causing its collapse. The major Oxfordian unconformity over northern Wrangellia (Jones et al, in press) is perhaps a result of such an impact, which propagated by basin closure(s) inward to precipitate the Nevadan orogeny. This view is posed as a question for regional workers to consider.

Finally, it must be emphasized that the configuration of the continental margin depicted in Figure 1 reflects post-Nevadan dispersion to a much greater extent than Nevadan or pre-Nevadan tectonics. The great northward displacements of the Stikinia and Wrangellia amalgams are evidence for such dispersion, which may have in effect removed most of the "Nevadan" orogen from the California region. Fragments of 160 m.y. rifting and spreading products may be lodged in northwestern Washington as scattered 160 m.y. arc-affinity ophiolitic nappes which arrived in mid- to Late Cretaceous time (Whetten et al, 1978, 1980). These may also attest to the importance of post-Nevadan dispersion.

Notable uncertainties in the relations depicted in Figure 5 relate to post-Nevadan dispersion. The first concerns the locus of the megashear through the northern Mojave-Sierra Nevada region. An observable link with the Josephine-Great Valley rift system cannot be made confidently owing to Cretaceous and Cenozoic dextral faults within and east of the Sierran metamorphic framework and batholith. Furthermore, geochemical and paleomagnetic data suggest at least 300 km (190 mi) and allow up to 1,000 km (620 mi) of post-Nevadan northward displacement of the Sierran ± Klamath metamorphic belt (Frei and Cox, 1983; Saleeby et al, in press). Dextral-sense structures within the Sierra Nevada thought to have formed by right-oblique convergence from Late Triassic through Cretaceous time (Saleeby, 1981) are resolved into differing Jura-Triassic and mid- to Late Cretaceous episodes by additional field and geochronological studies. Finally, paleomagnetic data from the Diablo segment of the Coast Range ophiolite are ambiguous and allow its genesis between paleoequatorial and California latitudes (Beebe and Luyendyk, 1983, and personal communication; Williams, 1983). In the case of an equatorial origin, the Coast Range ophiolite could be more directly linked to the southern megashear system (ancillary map, Fig. 5) suggested by Anderson and Schmidt (1983) to have extended through the present Mexican volcanic belt. This would imply that the southern Coast Range boundary structure (Fig. 5), or perhaps the main Great Valley lineament, functioned as a tremendously rapid dextral transform in Early Cretaceous time in the northward transport of the Coast Range ophiolite to its mid-Cretaceous forearc basin site. An equatorial origin for the Coast Range ophiolite might also explain the different sedimentary and structural histories of the Josephine and northern Coast Range ophiolites; notably, the latter did not experience the Nevadan orogeny and did not receive epiclastic sediments until the Upper Kimmeridgian (Hopson et al, 1981).

The three uncertainties discussed above draw attention to some of the first-order problems in Cordilleran accretionary tectonics. These include a rigorous understanding of the paleomagnetic data and in particular the interplay of physical and geological processes in rock magnetization and a better structural and stratigraphic understanding of post-Jurassic dispersion and its impact on earlier accretionary events. It is hoped that this paper has helped focus attention on these and other important problems.

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