Vol. 6, No. 2 February 1996

GSA TODAY

A Publication of the Geological Society of America

Alternate Origins of the Coast Range Ophiolite (California): Introduction and Implications

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ABSTRACT

Correctly interpreting the tectonic evolution of the California continental margin requires understanding the origin of the Jurassic Coast Range Ophiolite, which represents a fragment of mafic-to-ultramafic crust of oceanic character lying depositionally beneath the western flank of the Great Valley forearc basin in fault contact with the Franciscan subduction complex of the California Coast Ranges. Three contrasting hypotheses for genesis of the ophiolite as seafloor are each based on internally consistent logic within the framework of plate tectonics, but are mutually exclusive and lead to strikingly different interpretations of regional tectonic relations, even though each assumes that the Sierra Nevada batholith to the east represents the eroded roots of a magmatic arc linked to subduction along the Mesozoic continental margin. To encourage the further work or analysis needed to develop a definitive interpretation, summary arguments for each hypothesis of Coast Range Ophiolite genesis in mid- to late Jurassic time are presented in parallel: (1) backarc spreading behind an east-facing intraoceanic island arc that then collided and amalgamated with the Sierran continental-margin arc; (2) paleoequatorial mid-ocean spreading to form oceanic lithosphere that was then drawn northward toward a subduction zone in front of the Sierran continental-margin arc; and (3) forearc spreading within the forearc region of the Sierran continental-margin arc in response to transtensional deformation during slab rollback.

Multiple basaltic sills of the sheeted dike and sill complex, Point Sal remnant of the Middle Jurassic Coast Range ophiolite. The ridge in background exposes sheeted sills and (to left of tree on the skyline) base of the overlying pillow lavas.

INTRODUCTION

Widely distributed exposures of the Jurassic Coast Range Ophiolite in the California Coast Ranges represent deformed and structurally dismembered segments of oceanic crust and uppermost mantle now incorporated within the continental block (Bailey et al., 1970). The overall span of Middle to Late Jurassic radiometric ages for igneous components of ophiolite and postophiolite hypabyssal intrusions is ~170 to 155-150 Ma (Hopson et al., 1981, 1991; Saleeby et al., 1984; Mattinson and Hopson, 1992). Understanding correctly the origin and emplacement of the Coast Range Ophiolite is essential for understanding the Mesozoic evolution of the Cordilleran continental margin (Saleeby, 1992). The time is long past when geoscientists could assume that all ophiolites formed in the same way or have the same tectonic significance.

With the help of co-authors, we outline here three divergent views on the origin of the Coast Range Ophiolite. We emphasize that our areas of agreement are larger than our area of disagreement. We each interpret the Coast Range Ophiolite layered assemblage as a profile of mafic crust and lithosphere of oceanic character, and we infer that this profile was formed through magmatism induced by mantle upwelling linked to lithospheric extension or "spreading." We each also argue for emplacement of the ophiolite within the conceptual framework of plate tectonics, taking the Sierra Nevada composite batholith to the east to be the deeply eroded roots of Jurassic-Cretaceous magmatic arc belts, and regarding Franciscan rocks of the California Coast Ranges farther west as part of the subduction complex accreted near the trench that was paired with the Sierran-Klamath arc assemblage

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GSA TODAY *February 1996*
Vol. 6, No. 2

GSA TODAY (ISSN 1052-5173) is published monthly by The Geological Society of America, Inc., with offices at 3300 Penrose Place, Boulder, Colorado. Mailing address: P.O. Box 9140, Boulder, CO 80301-9140, U.S.A. Second-class postage paid at Boulder, Colorado, and at additional mailing offices. **Postmaster:** Send address changes to *GSA Today,* Membership Services, P.O. Box 9140, Boulder, CO 80301-9140.

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(Fig. 1). We concur that the east flank of the Franciscan subduction complex was thrust beneath and otherwise faulted against the Coast Range Ophiolite , which formed the westernmost segment of the floor of the Great Valley forearc basin lying between Sierran arc and Franciscan trench.

We nevertheless ascribe generation of the Coast Range Ophiolite to three different tectonic settings: (1) Dickinson infers "backarc" seafloor spreading behind a migratory east-facing intraoceanic island arc, which collided with the west-facing Sierran arc along the continental margin (as intervening oceanic lithosphere was consumed), to lodge the migratory arc and its backarc seafloor against the continental margin; (2) Hopson infers "midocean" seafloor spreading along an intraoceanic ridge crest, followed by tectonic transport of the resulting seafloor to the continental margin (as Sierran subduction drew it ever closer), until the ophiolite docked against the continental margin prior to the onset of Franciscan accretion; (3) Saleeby infers "forearc" seafloor spreading induced by transtensional deformation within the west-facing Sierran-Klamath arc system (in response to rollback of the subducted slab during highly oblique convergence).

The three concepts have quite different implications for details of tectonic history. For example, models 1 and 3 both involve varieties of so-called supra–subduction-zone ophiolite forming the floors of interarc basins, whereas model 2 envisions only "normal" seafloor spreading in an open ocean basin; models 2 and 3 involve only a single west-facing Sierran magmatic arc, whereas model 1 includes a separate east-facing arc that was accreted tectonically to the Cordilleran continental margin; models 1 and 2 both require tectonic transport of the ophiolite to the continental margin, whereas model 3 envisions genesis of the ophiolite in place within an arc-trench system lying along the continental margin.

We thank conveners R. G. Anderson, D. M. Miller, and R. M. Tosdal for arranging the 1993 Penrose Conference on Jurassic Cordilleran magmatism at which our opposing thoughts were pointedly juxtaposed, and we dedicate the following discussions to the memory of E. H. Bailey (who started it all).

1. COAST RANGE OPHIOLITE AS BACK-ARC–INTER-ARC BASIN LITHOSPHERE

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The concept that the Coast Range Ophiolite was formed by backarc-interarc spreading behind an east-facing intraoceanic island arc that was accreted to the continent in Jurassic time by arc collision along a suture within the Sierra Nevada foothills has persisted for 25 years (Moores, 1970; Schweickert and Cowan, 1975; Moores and Day, 1984; Ingersoll and Schweickert, 1986). Remnants of the intraoceanic arc complex are identified as thick submarine successions of deformed and disrupted Jurassic lavas and pyroclastics, as much as 5000 m thick (Bogen, 1985), resting locally on shreds of ophiolitic basement along the Sierran foothills belt. Eruptive activity in the foothills arc was coeval with Jurassic phases of magmatism in the west-facing Sierran continental-margin arc, whose axis lay farther east along and beyond the Sierran crest from mid-Triassic to mid-Jurassic time (Schweickert, 1976; Busby-Spera, 1988; Dilles and Wright, 1988). A strong case can be made that the Jurassic intraoceanic and continental-margin arcs of the

Ophiolite *continued on p. 3*

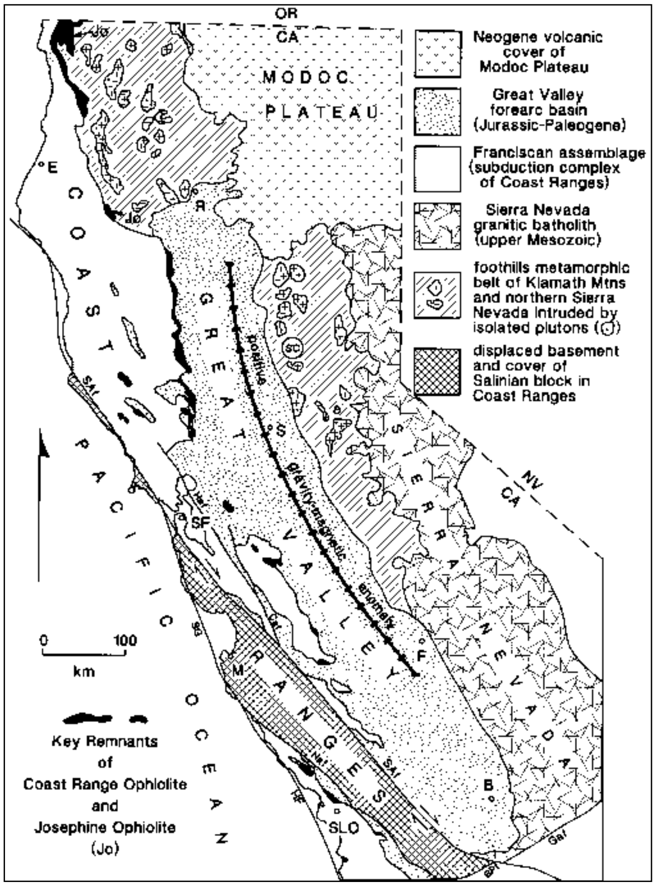

Figure 1. Geologic sketch map of part of California showing the regional relation of the Coast Range Ophiolite to key lithotectonic belts; SC—location of Smartville ophiolitic complex within foothills metamorphic belt; trend of Great Valley gravity-magnetic anomaly (high) after Cady (1975).

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Sierra Nevada are genetically unrelated (Dilek et al., 1990).

Deformed and variably metamorphosed Paleozoic-Mesozoic marine strata (mainly chert-argillite sequences and turbidites), exposed between and thrust beneath the two arc assemblages, are interpreted as a suture belt of compound subduction complexes cut by multiple fault zones and melange belts emplaced during arc-arc collision (Schweickert and Cowan, 1975). A modern example of a remnant ocean basin closing by face-to-face arc-arc collision is afforded by the Molucca Sea (Ricci et al., 1985). In the Sierran foothills belt, metamorphosed Upper Jurassic turbidites of the partly volcaniclastic Mariposa Formation are inferred to be an overlap assemblage deposited in part in a remnant ocean basin but also onlapping the accreted intraoceanic arc complex (Ingersoll and Schweickert, 1986). Once the foothills arc-arc suture belt had fully closed, subduction stepped outboard to the California Coast Ranges, trapping backarc-interarc Jurassic oceanic crust as the Coast Range Ophiolite at the leading edge of the overriding plate. With the onset of Franciscan subduction in the California Coast Ranges, Sierran arc magmatism also stepped westward to overprint both the foothills suture belt and the accreted intraoceanic arc.

The arc assemblage of the Sierran foothills metamorphic belt (Fig. 1) may represent a complex of related but disrupted arc segments and remnant arcs juxtaposed across fault contacts (Paterson et al., 1987; Edelman and Sharp, 1989). Volcanogenic successions locally overlie ophiolitic sequences of both earliest Jurassic (~210–200 Ma) and intra-Jurassic (~165–160 Ma) age (Saleeby, 1982; Saleeby et al., 1989; Dilek, 1989b; Edelman et al., 1989). The best preserved remnant of mafic crust occurs in the northwestern foothills within the Smartville ophiolitic complex (Fig. 1) formed by intra-arc rifting and associated magmatism during Middle to Late Jurassic time (Menzies et al., 1980; Beard and Day, 1987); combined radiometric and fossil ages bracket the main interval of its formation as 165–155 Ma (Day et al., 1985; Edelman and Sharp, 1989). Widespread overlap of foothills volcanic units by the Mariposa Formation near the Oxfordian-Kimmeridgian boundary implies that the arc complex had lodged along the foothills belt by ~155 Ma in Late Jurassic time (Schweickert et al., 1984). Crosscutting plutons of the evolving Sierran arc were emplaced into foothills volcanogenic assemblages and melanges by latest Jurassic or earliest Cretaceous time (~150–140 Ma) (Saleeby et al., 1989).

Recent interpretations that the foothills arc complex was accreted to the continental margin prior to formation of the Smartville complex, which is then interpreted as the product of spreading in place within the west-facing Sierran forearc (Dilek, 1989a; Edelman et al., 1989), rely upon the presence in the northern foothills belt of Middle Jurassic (~165 Ma) granitoid plutons that cut thrusts placing Lower Jurassic elements of the foothills arc assemblage above metasedimentary melange. The resulting conclusion that accretion of the foothills arc complex was complete by Middle Jurassic time is not robust, however, because the intruded melange unit is not tied firmly to the continent and underthrusting of the eastern flank of an east-facing intraoceanic arc by melange would be expected prior to final suturing to the continent. Arc plutons unrelated to the Sierran continental arc could thus cut arc-melange thrusts in the late phases of intraoceanic arc evolution prior to accretion along the compound subduction complex of the foothills belt. Widespread Middle Jurassic deformation within the Sierran continental arc has been attributed in part to terrane accretion (Edelman and Sharp, 1989; Edelman et al., 1989), but could as well reflect intra-arc contraction.

Several workers (Shervais and Kimbrough, 1985; Shervais, 1990; Stern and Bloomer, 1992) have concluded that the Coast Range Ophiolite has geochemical affinities with supra–subduction-zone (SSZ) ophiolites (Pearce et al., 1984), implying the influence of a subducted slab on its generation. These workers and others (Evarts, 1977; Lagabrielle et al., 1986; Robertson, 1989) have variously inferred backarc, forearc, or intra-arc settings of either east-facing or west-facing arcs for its origin. Ophiolitic breccias locally overlying the Coast Range Ophiolite and resting concordantly beneath the Great Valley Group reflect local but widespread extensional deformation at the sites of their formation (Robertson, 1990). Following initiation of Franciscan subduction to the west, Great Valley forearc sedimentation was underway near the Kimmeridgian-Tithonian boundary (155–150 Ma).

Stern and Bloomer (1992) argued the case for forearc spreading to produce the Coast Range Ophiolite by drawing an analogy between the Jurassic Sierran arc and early stages in the evolution of the modern Izu-Bonin-Mariana arc of the western Pacific. As they note, however, the analogy is not exact because the concepts of “subduction-zone infancy” and “infant-arc crust,” unquestionably applicable to the Eocene Izu-Bonin-Mariana arc, cannot apply to the Sierran arc, for which abundant radiometric ages for plutons indicate arc activity throughout the interval 215–80 Ma (Stern et al., 1981; Chen and Moore, 1982). Moreover, the Izu-

Ophiolite *continued on p. 4*

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Bonin-Mariana arc is indisputably an intraoceanic arc, and geochemical analogies between the Coast Range Ophiolite and igneous rocks of the Izu-Bonin-Mariana system can be interpreted as strong evidence for origin of the former in close relation to an intraoceanic arc, rather than to the Sierran arc along the continental margin. Recent work near intraoceanic island arcs in the southwest Pacific has shown the difficulty of distinguishing geochemically among arc-related magmas erupted in backarc, intra-arc, and forearc settings (Hawkins, 1994).

Accordingly, origin of the Coast Range Ophiolite by backarc spreading behind an intraoceanic island arc that lodged in the Sierran foothills late in Jurassic time remains a viable hypothesis. Scraps of remnant arc structures within the ophiolite are to be expected in this case, along with overall SSZ geochemistry. If forearc rifting of the Sierran arc (model 3) were the correct interpretation, one would expect to find rifted fragments of prerift Sierran foothills melange units within the Coast Ranges, but such has never been reported. Moreover, the Coast Range Ophiolite is capped locally, as at Llanada, by ~1500 m of intermediate volcaniclastic rocks (Robertson, 1989; Hull et al., 1993), which could readily be derived from a rifting intraoceanic arc but are unlike chert-rich quartzolithic Upper Jurassic to Lower Cretaceous sandstones derived from a Sierran provenance and deposited in both the Mariposa Formation of the foothills belt and at lower horizons of the Great Valley forearc basin (Ingersoll, 1983; Short and Ingersoll, 1990). Upward transitions from distal to proximal volcaniclastic strata above the Coast Range Ophiolite are interpreted here as the result of progradation from arc sources, rather than the record of tectonic transport toward the arc (as in model 2).

If the Coast Range Ophiolite, as argued here, is an accreted fragment of backarc-interarc crust, then its formation at essentially the same time as the intra-arc Smartville complex of the Sierran foothills reflects the same general interval of extensional tectonism within an intra-oceanic arc-trench system. The rather mafic crustal profile of the intervening Great Valley (Cady, 1975; Holbrook and Mooney, 1987) can be understood as representing similar ophiolitic materials, perhaps telescoped by deformation during accretion and certainly overprinted by subsequent Sierran plutonism. Recent interpretations of paleomagnetic data for several remnants of the Coast Range Ophiolite suggest paleolatitudinal concordance with North America (Butler et al., 1991; Mankinen et al., 1991; Hagstrum and Murchey, 1993), requiring no major north-south transport (model 2) but not precluding east-west transport behind an arriving island arc.

Pillow basalt with interpillow pelagic limestone. Volcanic member of the Middle Jurassic Coast Range ophiolite, Llanada remnant, southern Diablo Range, California.

Two residual questions remain. The first pertains to relations between the Sierran foothills belt and the Klamath Mountains, where the Josephine Ophiolite is inferred to have formed by interarc spreading along the continental margin within the interval 165–155 Ma (Saleeby et al., 1982; Harper and Wright, 1984; Wyld and Wright, 1988). This interval overlaps the time span inferred above for arc rifting within an offshore intraoceanic arc complex to form the Smartville complex and Coast Range Ophiolite. In the Klamaths, however, the Rogue Volcanics form a frontal arc coeval with the interarc basement of the Josephine Ophiolite, whereas no analogous assemblage has been discovered within the Coast Ranges. Spreading to form the Josephine Ophiolite may have been a response to arc-arc collision in the Sierran region farther south (Ingersoll and Schweickert, 1986).

The second issue pertains to the time of initiation of Franciscan subduction west of the Coast Range Ophiolite. Ages (K-Ar, U-Pb, Ar-Ar) of high-grade blueschist blocks within the Franciscan assemblage range from 140–145 to ~160 Ma (Wakabayashi, 1992). The oldest ages appear to overlap with the final phases of formation of the Smartville complex and Coast Range Ophiolite, whereas the tectonic model favored here holds that Franciscan subduction should postdate accretion of those intra-arc and backarc features by arc-arc collision in the Sierran foothills. Perhaps resolution of this paradox lies in a better understanding of the mechanisms by which subduction was arrested in the Sierran foothills and initiated in the Coast Ranges to the west. Some overlap in the timing of those two events is not difficult to envision as an intraoceanic arc system gradually lodged firmly against the continental margin.

2. COAST RANGE OPHIOLITE AS PALEOEQUATORIAL MID-OCEAN LITHOSPHERE

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The igneous pseudostratigraphy, structure, seismic velocity profile, petrology, and geochemistry of the mid-Jurassic (~170–165 Ma) Coast Range Ophiolite seem consistent with tectonically thinned, multiply altered oceanic crust, but provide no clear-cut guide to original tectonic setting. Lacking decisive evidence from the igneous rocks, we turn to the associated Jurassic sedimentary rocks. The succession of sediments entrapped within and accumulating on top of the igneous crust of a mobile oceanic plate make up its *plate stratigraphy* (Berger and Winterer, 1974), which is applicable to ophiolites and can provide a travel history for an ancient oceanic plate. For example, the plate stratigraphy of ophiolites formed at a divergent plate margin (mid-ocean ridge) will reflect transport *toward* a convergent margin, marked by progressive increase in the sedimentary products of arc

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Ophiolite *continued from p. 4*

volcanism. Arc-related ophiolites, born behind convergent plate margins (i.e., above subduction zones), lie adjacent to arc volcanism from birth. Their travel histories might keep them close to the active arc (e.g., arc-parallel strike-slip transport) or take them farther away in the case of prolonged back-arc spreading, but will not carry them toward the arc from a distant birthplace.

Jurassic plate stratigraphy at the Point Sal, Stanley Mountain, Cuesta Ridge, and Llanada Coast Range Ophiolite remnants (Fig. 1) shows that the igneous oceanic crustal rocks originated beyond reach of terrigenous or volcanic arc sedimentation and were then carried progressively closer to the coeval Jurassic arc that fringed western North America. The lithostratigraphic succession begins with the sedimentary rocks entrapped as small scraps within the ophiolite volcanic member. These are mainly basaltic rubble, red jasper (silicified ferruginous hydrothermal sediment), and pelagic limestone. Limestone is the only externally derived sedimentary rock, indicating an open-ocean setting. Claims of arc-derived volcaniclastic strata interbedded with Coast Range Ophiolite lavas are incorrect; those strata belong to the unconformably overlying Late Jurassic (volcanopelagic) (VP) succession (see below), locally isolated between subvolcanic *intrusive* sheets (postophiolite sills, mistaken for ophiolite lava flows) that commonly concentrate along and just above the Coast Range Ophiolite–VP contact in some Coast Range Ophiolite remnants.

Resting depositionally on the ophiolite lava is an Upper Jurassic (Oxfordian-Tithonian) *VP succession* (Hull et al., 1993) composed mainly of two original components: radiolarian ooze and rhyolitic to andesitic volcaniclastic marine sediment. Most VP remnants consist of a thin (50–130 m) *tuff-radiolarite facies* of tuffaceous radiolarian mudstone and chert, and altered tuffs representing submarine deposits of pyroclastic fallout (airborne tephra) mixed in varying proportions with radiolarian ooze. A thick upper *sandy-fragmental facies* composed of up to 300 m of bedded pumiceous and lithic lapilli tuff, volcaniclastic sandstone (including turbidites) and conglomerate, with interbeds of radiolarian tuffaceous mudstone, overlies the *tuff-radiolarite facies* at some central Coast Range localities (Llanada–Del Puerto–Hospital Creek), and locally (Llanada) grades up into an additional 500 m of cobbly to bouldery andesitic submarine debris-flow deposits capped by tuffaceous radiolarian chert. The tuff-radiolarite facies represents the submarine *distal tephra fringe* of an active, emergent volcanic arc; the upper sandy-fragmental facies is the corresponding coarser *proximal submarine apron.* This succession reflects transport of the oceanic plate (Coast Range Ophiolite) through the distal tephra fringe (VP tuff-radiolarite facies) downwind of an active Jurassic arc, then partly into the proximal volcaniclastic submarine apron (VP sandy-fragmental facies).

The Coast Range Ophiolite–VP contact is *unconformable*: pillow lavas below this contact carry interpillow limestone, whereas VP strata immediately above are mixtures of radiolarian ooze and volcanic ash. The unconformity marks a depositional hiatus (Fig. 2) that began when spreading carried Coast Range Ophiolite oceanic crust below the calcite compensation depth (CCD), ending carbonate deposition, and lasted until its entry into the tephra fringe of an arc. The Upper Jurassic and Cretaceous *Great Valley Group* of terrigenous clastic marine strata overlies the VP succession conformably. The uppermost Jurassic lower portion of the Great Valley Group, composed of mudstone with interbeds of turbiditic siltstone and sandstone, plus local lenticular (channel-fill) pebble conglomerate well above the base of the succession (Bailey et al., 1964; Page, 1972; Suchecki, 1984), correspond to submarine slope deposits prograding over basin-plain deposits (Suchecki, 1984). These basal Great Valley Group strata, derived from Klamath-Sierran tectonic highlands at the North American accretionary margin (Dickinson and Rich, 1972; Ingersoll, 1983), represent a terrigenous clastic apron that prograded over the deep ocean floor (Coast Range Ophiolite–VP succession) following onset of the Nevadan orogeny (Pessagno et al., 1996).

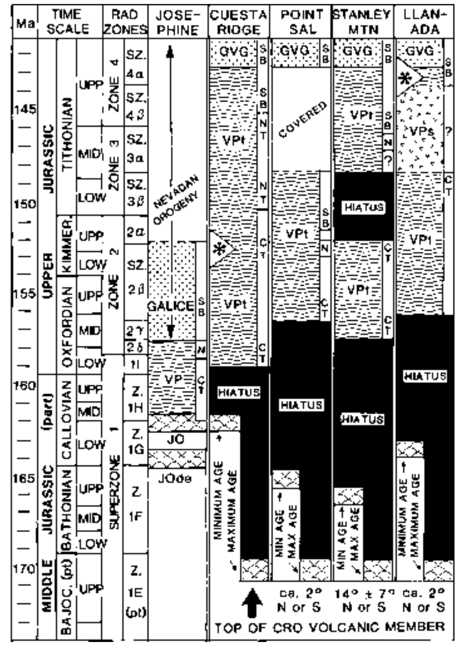

Figure 2. Tectonostratigraphic diagram comparing Coast Range Ophiolite (CRO) –VP– basal Great Valley Group (GVG) succession at Cuesta Ridge, Point Sal, Stanley Mountain, and Llanada with the Josephine Ophiolite (JO)–Galice succession. Time scale from Gradstein et al. (1994); top of the Jurassic from Bralower et al. (1990); radiolarian zonation from Pessagno et al. (1993). Minimum and estimated maximum possible ages of Coast Range Ophiolite remnants (only tops shown) are based on U/Pb and Pb/Pb isotopic ages, respectively (Mattinson and Hopson, 1992). The Josephine Ophiolite age is from Harper et al. (1994); Devils Elbow outlier (JODE) age from Wyld and Wright (1988). Black intervals span the depositional hiatus between Coast Range Ophiolite remnants and the overlying VP succession; also a hiatus within VP. VP spans time of volcanopelagic sedimentation including distal tuffaceous (VPt) and proximal sandy-fragmental (VPs) facies, respectively. Terrigenous sedimentation on Coast Range Ophiolite–VP began with basal strata of the Great Valley Group in the latest Jurassic. The GALICE interval spans the terrigenous graywacke-mudstone sequence above Josephine Ophiolite and thin VP strata. Nevadan orogeny (Klamath phase) from Harper et al. (1994). CT interval spans sedimentation in Central Tethyan Province, NT in Northern Tethyan Province, and SB in Southern Boreal Province; question-mark intervals lack diagnostic radiolarians. Asterisk wedges mark Late Jurassic magmatic (intrusive) and hydrothermal events.

Interpillow pelagic (coccolithic) limestone near the top of the upper lava, Point Sal remnant of the Coast Range ophiolite, Santa Barbara County, California.

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Ophiolite *continued from p. 5*

We accordingly infer that the Coast Range Ophiolite formed at a spreading center in an open-ocean region of pelagic carbonate sedimentation. Seafloor spreading carried Coast Range Ophiolite crust to sub-CCD abyssal depths, ending pelagic carbonate deposition for up to ~12 m.y. (Fig. 2), then into a realm of oceanic upwelling where radiolaria flourished and radiolarian ooze deposition began. This coincided approximately with entry into the distal tephra fringe of an active volcanic arc, where airborne ash mixed with radiolarian remains in the water column. Most parts of the mobile Coast Range Ophiolite plate moved through only the tephra fringe of the arc, accumulating radiolarian ooze and mainly fine ash (Fig. 2, VP tuff-radiolarite facies). But part of the Coast Range Ophiolite plate approached the volcanic arc more closely, passing first through its deep-sea tephra fringe and then into its proximal apron of volcaniclastic turbidites and debris flows (Fig. 2; Llanada remnant). Following VP arc sedimentation, which ended in the late Tithonian, latest Jurassic terrigenous turbidites and muds from Klamath-Sierran accreted terranes advanced out over the deep ocean floor. This Jurassic Coast Range Ophiolite–VP–basal Great Valley Group oceanic succession, uplifted when Franciscan subduction began farther outboard, then floored the new Cretaceous forearc basin.

A mobile interpretation of Coast Range Ophiolite–VP oceanic crust also stems from paleomagnetic and faunal evidence of large-scale Jurassic paleolatitudinal displacement indicated by (1) paleomagnetic measurements on pillow lavas at three Coast Range Ophiolite remnants, and (2) provinciality of radiolarian and molluscan faunas in VP–Great Valley Group strata that correlate roughly with paleolatitude. Paleoinclinations of remanent magnetism in Coast Range Ophiolite pillow lavas at Stanley Mountain (McWilliams and Howell, 1982), Point Sal, and Llanada (Beebe, 1986; Pessagno et al., 1996) were acquired in the Jurassic paleoequatorial region. Lower VP strata that rest on the Coast Range Ophiolite remnants consistently have *Central Tethyan* radiolarian assemblages, whereas progressively higher VP strata have Northern Tethyan and then *Southern Boreal* radiolarian assemblages, respectively (Fig. 2; Pessagno et al., 1996). Molluscans (Buchias) and radiolarians of the overlying Great Valley Group strata are Southern Boreal. Boundaries between Central Tethyan, Northern Tethyan, and Southern Boreal provinces are placed at approximately lat 22°N and 30°N, respectively, on the basis of global distributions of molluscan, radiolarian, and calpionelid faunas (e.g., Pessagno et al., 1987). These data show that the mid-Jurassic Coast Range Ophiolite oceanic crust formed near the paleoequator and was transported northward, passing progressively through Central Tethyan, Northern Tethyan, and Southern Boreal provinces during VP sedimentation in the Late Jurassic (Fig. 2).

Coast Range Ophiolite–VP remnants at Cuesta Ridge and Llanada (also Del Puerto) host swarms of Upper Jurassic basaltic-diabasic, keratophyric-microdioritic and quartz keratophyric–granophyric sills and dikes, and are overprinted by hydrothermal metamorphism. The widespread assumption that ophiolite genesis (mid-Jurassic) and pyroclastic arc volcanism were contemporaneous and closely adjacent, and consequently that the ophiolite formed near or within an active arc (Evarts, 1977; Evarts and Schiffman, 1982; Robertson, 1989), comes from the occurrence of sills (mistaken for ophiolite lava flows), dikes, and hydrothermal alteration within the VP succession. This interpretation is now rendered untenable by (1) recognition of the Coast Range Ophiolite–VP unconformity with a long depositional hiatus, (2) identification of supposed “ophiolite lava flows interbedded with arc volcaniclastics” as sills invading Upper Jurassic strata and yielding Late Jurassic radiometric ages, and (3) evidence that the Late Jurassic “sill event” took place at more northerly paleolatitudes than creation of Coast Range Ophiolite oceanic crust (Fig. 2).

The lithostratigraphic columns of Figure 2 can be used as map tracklines for individual segments of moving Coast Range Ophiolite oceanic lithosphere. The assemblage of tracklines, positioned geographically according to constraints imposed by the lithofacies succession, paleolatitude–faunal province, and age of each member, show the trajectories of individual segments of an oceanic plate moving from their origin through a succession of sedimentary environments toward the consuming plate margin (Fig. 3). We conclude that (1) the Coast Range Ophiolite is exotic to the Jurassic North American continental-margin arc; (2) the trackline assemblage cannot be fitted into a backarc, forearc, or infant-arc association; (3) the Coast Range Ophiolite–VP tracklines (plate motion) must be oriented approximately north-northeast–south-southwest to fit the age–paleolatitude–faunal province constraints; (4) the tracklines indicate dextral oblique subduction of oceanic lithosphere beneath the northwest-trending Jurassic arc system, (5) the subduction zone lay between the arc and VP tephra fringe, the trench forming a barrier to all but *airborne* volcaniclastic materials until the trench filled and was overlapped in late Tithonian time (Fig. 2; Llanada remnant) following the main pulse of the Nevadan orogeny; (6) the Late Jurassic subduction zone lies buried beneath California's Great Valley and thrust sheets of the Klamath Mountains; (7) the 162–164 Ma Josephine ophiolite (Figs. 1 and 2), formed in the backarc region behind the Middle to Late Jurassic Rogue-Chetco arc of the Klamath region (Harper, 1984; Harper et al., 1994), and is not related to the Coast Range Ophiolite; and (8) the diachronous Late Jurassic subvolcanic igneous and hydrothermal events took place beneath deep sea floor during VP sedimentation, and may represent rift-tip propagation of a new, Late Jurassic oceanic rift system through the older (mid-Jurassic) Coast Range Ophiolite plate (Hopson et al., 1991).

3. COAST RANGE OPHIOLITE AS PARAUTOCHTHONOUS FOREARC LITHOSPHERE

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The forearc generation model for the Coast Range Ophiolite is based on petrochemical and stratigraphic features of the ophiolite, relations of coeval ophiolitic and arc rocks of the western Klamath Mountains and Sierra Nevada, and consideration of relations in west Pacific fringing arc systems. A corollary of the forearc generation model is that at relatively short time scales (~5 m.y.) juvenile forearc crust may find itself residing either within an interarc basin or within the locus of arc construction. Such changes in tectonic setting may arise from evolving loci of arc construction working in series with the production of juvenile ophiolitic crust, and in the case of oblique subduction the tangential migration of active and inactive arc segments and basinal tracts into (and out of) ephemeral juxtapositions. This corollary and its possible application to the Coast Range Ophiolite is demonstrated by the nearby Josephine Ophiolite of the western Klamaths (Fig. 1). The Josephine Ophiolite may be broadly correlative with the northern Coast Range Ophiolite (Saleeby, 1981, 1992), but the former is easier to interpret because it is preserved in its emplacement configuration with little modification. In contrast, the Coast Range Ophiolite has been severely modified by Franciscan underthrusting and extensional attenuation (Jayko et al., 1987).

The Josephine Ophiolite formed in a transtensional basin that initially opened along the forearc edge of the Sierran-Klamath Middle Jurassic arc (Saleeby, 1982; Harper and Wright, 1984; Wyld and Wright, 1988; Saleeby and Harper, 1993). This arc was constructed in large part over a polygenetic basement of older ensimatic assemblages that were previously accreted

Ophiolite *continued on p. 7*

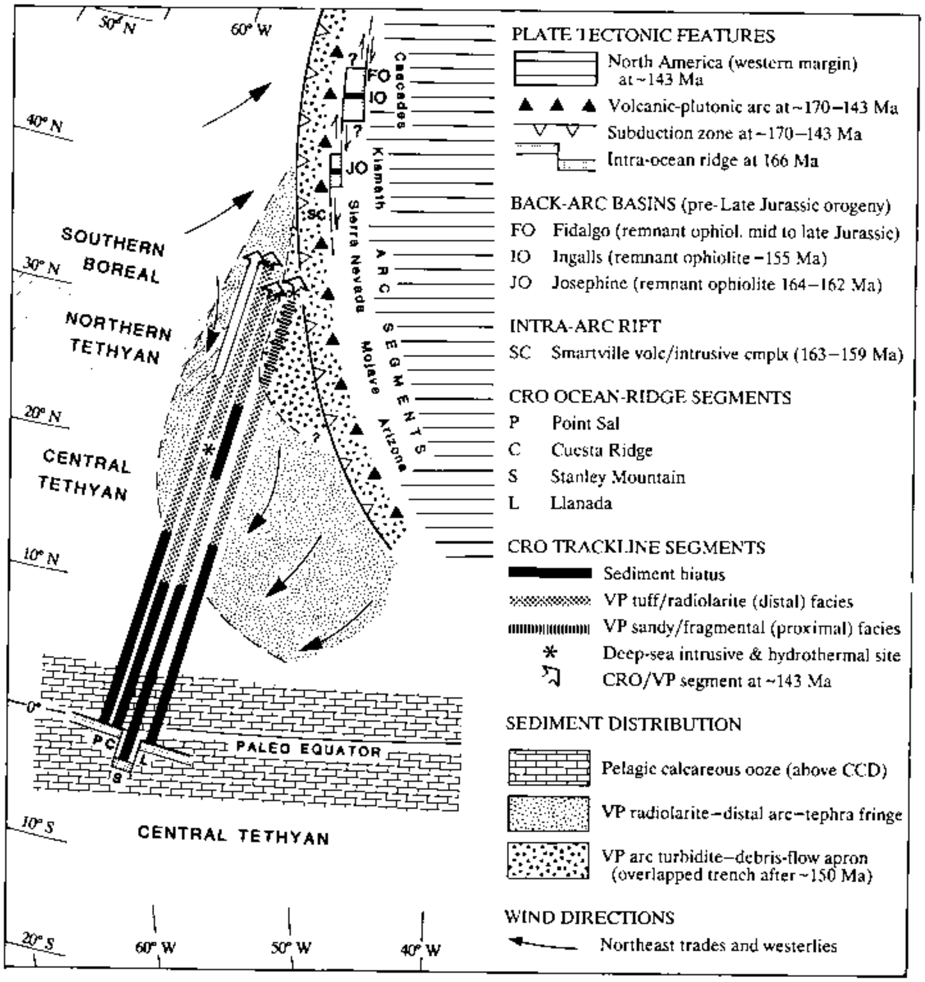

Figure 3. Eastern Pacific–western North America region showing key tectonic elements for part of Middle to latest Jurassic time (~166–143 Ma). Tracklines of Point Sal (P), Cuesta Ridge (C), Stanley Mountain (S), and Llanada (L) Coast Range Ophiolite segments trace their progression by sea-floor spreading from a 166 Ma paleoequatorial midocean ridge spreading center through deep-sea regions of (1) sub-CCD calcareous ooze starvation, (2) volcanopelagic sedimentation, to (3) their 143 Ma positions (arrowheads) just prior to burial beneath terrigenous clastic sediments (basal Great Valley Group) from the adjacent Nevadan orogen. Trackline positions and direction are constrained by data combined in Figure 2: the lithostratigraphy, biostratigraphy, Coast Range Ophiolite radiometric ages and paleomagnetic latitudes, and VP faunal provinces. Location of western North America at 143 Ma from Scotese and Denham (1988), modified to paleolatitudes of May et al. (1989). Triangles mark trend of Upper Jurassic arc volcanics and plutons. Jurassic subduction zone in front of the arc placed at the California Great Valley magnetic-gravity high (Fig. 1), where mafic high-velocity crust dips eastward beneath the Sierra Nevada (Mooney and Weaver, 1989); projection northward and southward is schematic. VP distal tuffaceous facies (from airborne tephra and radiolarian ooze) accumulated outboard of the Jurassic trench. VP proximal sandy-fragmental facies (volcaniclastic turbidites and debris flows) accumulated inboard, bounded by the trench until it filled in latest Jurassic time (see text). JO, IO, and FO schematically depict Middle to Late Jurassic back-arc basins whose oceanic crust–mantle remnants are the Josephine, Ingalls, and Fidalgo ophiolites (Harper, 1984; Miller et al., 1993). SC marks the Smartville intra-arc igneous complex (Beard and Day, 1987).

Ophiolite *continued from p. 6*

to the Cordilleran plate edge; to the southeast the arc tracks onto North American continental lithosphere, which prior to active-margin tectonism had been thinned by passive-margin formation. As Josephine Ophiolite forearc spreading progressed, arc magmatism to the east waned. By the cessation of spreading, arc magmatism relocated along the outer edge of the Josephine Ophiolite basin, capping both rifted screens of older Klamath (or Sierran) terranes and part of the Josephine Ophiolite basin floor. The entire system was then imbricated and crosscut by plutons during the Late Jurassic Nevadan orogeny. The forearc spreading generation, inter-arc basin residence, and thrust imbrication of the Josephine Ophiolite all occurred within ~10 m.y.

Geophysical and basement core data indicate that the Great Valley is underlain primarily by oceanic crust (Cady, 1975; Saleeby et al., 1986). These geophysical data as well as stratigraphic relations along the margins of the valley indicate that at least the western part of the valley is floored by the Coast Range Ophiolite, and that the eastern margin of the valley is floored by coeval mafic submarine arc strata of the western Sierra Nevada. These arc rocks and their polygenetic basement are cut by swarms of sheeted and individual dikes that are the same age as the Coast Range Ophiolite and Josephine Ophiolite, and which mark the waning of Middle Jurassic arc activity in this region (Saleeby, 1982, 1992; Saleeby et al., 1989). The forearc spreading model for the Coast Range Ophiolite considers these westernmost Sierran rocks to be the inner boundary of the Coast Range Ophiolite–Josephine Ophiolite basin system. As discussed below, the Josephine and Coast Range Ophiolites appear to have migrated northward shortly following spreading genesis, roughly placing the Josephine Ophiolite outboard of the western Sierra Nevada and the Coast Range Ophiolite farther south during basin formation. Unlike the Josephine Ophiolite segment of the basin system, the Coast Range Ophiolite–Great Valley segment survived the Nevadan orogeny. This difference may reflect ~100 km of eastward underthrusting of Josephine Ophiolite–related rocks beneath the central Klamaths following and partly in conjunction with northward translation (Saleeby and Harper, 1993); analogous underthrusting is not directly observed, nor imaged geophysically, for the Coast Range Ophiolite–Great Valley segment. The forearc spreading model thus considers the modern morphologic Great Valley as a partial remnant of the original basin.

The forearc spreading model implies that the Coast Range Ophiolite formed in a supra–subduction-zone (SSZ) setting, as suggested by abundant geochemical data (Shervais and Kimbrough, 1985; Shervais, 1990). An SSZ setting is further suggested by the presence of arc-derived pyroclastic, volcaniclastic, and hypabyssal material expressed mainly in the later phases of the Coast Range Ophiolite igneous and sedimentary succession (referenced in model 2). These later arc components are analogous to the constructional arc products that migrated westward to the outer fringes of the Josephine Ophiolite basin. The absence of rifted screens of older basement in the Coast Range Ophiolite (as noted in model 1) may stem from the limited outcrop area of the Coast Range Ophiolite relative to the probable original basin size.

The difficulties with model 1, which also envisions SSZ affinity, are outlined as follows (after Saleeby and Busby-Spera et al., 1992): (1) The implied Late Jurassic (Nevadan) collisional suture within the western Sierras and Klamaths cannot be

Ophiolite *continued on p. 8*

Tuffaceous radiolarian chert within the *tuff/radiolarite facies* of the Upper Jurassic volcanopelagic succession, lying unconformably on pillow lava (not shown) of the Middle Jurassic Coast Range ophiolite. Point Sal Coast Range Ophiolite–VP remnant, Santa Barbara, California.

Ophiolite *continued from p. 7*

delineated with confidence; the most likely structures are pre-Callovian (>169 Ma) in age, as indicated not only by local crosscutting relations of plutons but also by the occurrence of a regional belt of Middle Jurassic dioritic to peridotitic arc plutons that cut across the depositional basement of both hypothetical east- and west-facing arcs. (2) The entire subduction complex and forearc region of the postulated east-facing arc is missing; Tethyan limestone-bearing melange units purported to represent a sandwiched subduction complex reside as depositional basement for Jurassic arc rocks and thus represent an earlier phase of tectonic accretion. (3) Likewise, the Middle Jurassic forearc and subduction complex for the implied west-facing system are missing; the best candidates for such rocks are cut by copious Middle Jurassic arc plutons and, in the northern Sierra, are part of the depositional basement of Lower and Middle Jurassic arc strata. (4) Rock assemblages along the Sierran crest and farther east, considered to be the axial Jurassic arc, are dominated by silicic ignimbrites and by plutonic suites with scattered backarc geochemical affinities; the axis of the arc more likely lay farther west, represented in part by the regional belt of dioritic to peridotitic plutons, and in part by the western Sierran mafic arc strata. (5) The polarity of migration for constructional arc components is opposite to that expected for an east-facing arc–backarc basin–remnant arc system; migration was westward across the Coast Range Ophiolite basin following spreading and Sierran arc waning, analogous to the western Klamath pattern.

An in-situ forearc spreading model based on the early stages of the Eocene Izu-Bonin-Mariana system was also offered for the Coast Range Ophiolite by Stern and Bloomer (1992). They postulated that rapid slab rollback pulled forearc extension, and that this resulted from the subduction of an older cooler transform wall that was adjacent to the oceanic fracture zone along which subduction nucleated. The details of this mechanism encounter difficulty for the Coast Range Ophiolite, as discussed in model 2. An alternative, yet fundamentally similar slab rollback mechanism for the Coast Range Ophiolite is the subduction of old, cold Panthalassan lithosphere inherited from the Pangea regime (Saleeby and Busby-Spera et al., 1992). Upper-plate extension along the southwest Cordilleran plate edge may be recorded as far back as Early Jurassic time by earlier phases of forearc magmatism (Saleeby, 1992) as well as a tendency for much of the arc magmatism to have expressed itself by silicic ignimbrite ponding within a largely submarine graben depression system (Busby-Spera, 1988). The single largest pulse of ignimbrite ponding along the eastern Sierra Nevada corresponds precisely in time with the formation of the Coast Range and Josephine Ophiolites as well as the western Sierra dike swarms. We thus suggest that the broadly extensional arc-forearc region intensified in its extensional deformation toward the end of the Middle Jurassic, resulting in the production of ophiolitic forearc crust in the wake of the foundering slab. This analysis considers the dynamics of the subducting plate to be the prime factor in promoting forearc spreading.

As mentioned above, the Josephine Ophiolite and particularly the southern Coast Range Ophiolite, like many outer Cordilleran terranes, appear to record resolvable northward transport in Middle Jurassic time (model 2 discussion and reviewed in Saleeby and Busby-Spera, et al., 1992). We interpret these displacements to reflect the tangential sense and approximate magnitude of the oblique subduction of Panthalassan lithosphere during Middle Jurassic time. Northward transport of the Coast Range and Josephine Ophiolites is postulated to have occurred above the Cordilleran subduction zone within an oblique spreading basin system analogous to the active Andaman Sea (Curray et al., 1979). Taking into account superposed Late Cretaceous to Holocene disruptions, the Coast Range Ophiolite–Josephine Ophiolite basin system may have represented ~2000 km of the forearc (and ephemeral inter- to intra-arc) region along the Cordilleran plate edge. Available constraints on spreading kinematics recorded within the Josephine Ophiolite, and locally within the Coast Range Ophiolite, are permissive of a strong spreading component subparallel to the plate edge, suggesting that tangential transport was dynamically linked to spreading (Harper et al., 1985; Saleeby, 1992). Furthermore, regional linear gravity-magnetic anomalies oriented along the axis of the Great Valley (Fig. 1) may be modeled as a fossil transform system within the basin floor. Such longitudinal transform(s) could have served as zones of terrane removal as well as ophiolite accretion and translation (Saleeby and Busby-Spera, et al., 1992). Stratigraphic differences between Josephine Ophiolite and Coast Range Ophiolite can be reconciled with the northward transport model. Overlapping volcanic-poor turbidites are of Oxfordian-Kimmeridgian age above the Josephine Ophiolite and its fringing arc, and similar strata of the lowermost Great Valley Group young southward from late Kimmeridgian to Tithonian age above the Coast Range Ophiolite and its overlapping arc strata. In the western Sierra Nevada, similar strata locally range back to Callovian in age. These units are interpreted as different parts of a regional progradational submarine fan system derived from northerly Middle and Late Jurassic highlands and spread southward, first across the western Sierran belt and then sequentially across the Josephine Ophiolite and Coast Range Ophiolite as the various segments of the basin system migrated into their resting sites (Saleeby and Busby-Spera, et al., 1992).

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Manuscript received July 1, 1995; revision received September 19, 1995; accepted September 20, 1995. ■

WASHINGTON REPORT

Bruce F. Molnia

Washington Report provides the GSA membership with a window on the activities of the federal agencies, Congress and the legislative process, and international interactions that could impact the geoscience community. In future issues, Washington Report will present summaries of agency and interagency programs, track legislation, and present insights into Washington, D.C., geopolitics as they pertain to the geosciences.

Farewell, U.S. Bureau of Mines

"The U.S. Department of Interior will recognize the accomplishments and honor the contributions of the U.S. Bureau of Mines in a commemorative ceremony Wednesday, December 13, 1995. The ceremony will focus on the research and achievements made by the 85 year old agency, slated for closure January 8, 1996, as a result of GOP budget cuts."

—Department of Interior Media Advisory, December 11, 1995

"When I accepted the responsibilities and challenges of being the 19th Director of the U.S. Bureau of Mines, I did so as a scientist who believes that scientists should invest in scientific leadership. It is critical that the focus of our research investments be on solving problems, rather than lost in conflict and chaos. I have observed threats to that focus for our nation that are truly staggering. We are a nation who relies on science and technology, yet we run away from science and technology leadership. First, the Office of Technology Assessment; second, the U.S. Bureau of Mines; third, who knows? Given the impasse in budget resolution over the past two and a half months, we should ask, 'How are we going to refocus our science and technology spending so that the national interest is the common ground?'"

—Bureau of Mines Director Rhea L. Graham, December 13, 1995

On December 13, 1995, the last workday before the start of the prolonged shutdown of the Federal Government, the Department of the Interior (DOI) paid tribute to the employees of the U.S. Bureau of Mines (USBM) for 85 years of outstanding public service and dedication to improving technology and protecting human resources.

In October 1995, as part of the budget appropriations process, the Congress voted to terminate all of the USBM programs in 90 days. It also directed that the USBM's health and safety research program activities be transferred to the Department of Energy, that some of its information analysis activities be transferred to the U.S. Geological Survey, and that the Mineral Land Assessment in Alaska be transferred to the U.S. Bureau of Land Management. USBM's helium program will be administered by the Secretary of the Interior until its proposed privatization is completed by 1997. Almost $100 million of USBM 1995 programs and activities were eliminated and 1200 employees separated. Discontinued programs include pollution prevention and control, environmental waste remediation, minerals land assessment, and minerals availability.

Facilities and offices that were closed are located at Spokane, Washington; Reno, Nevada; Salt Lake City, Utah; Denver, Colorado; Tuscaloosa, Alabama; Rolla, Missouri; Minneapolis, Minnesota; and Washington, D.C. The 90-day time line expired on January 8, 1996. At the commemoration, Secretary of the Interior Bruce Babbitt stated, "The Bureau of Mines has pioneered award-winning research and developed technologies to improve the life for the country in many areas. Their research and development helped to detect and prevent fires, reduce silica and coal dust exposure, prevent mine cave-ins, and reengineer dangerous practices and equipment to create a safer environment. The Bureau has played key roles in improving and protecting the health and safety of mine operators." Secretary Babbitt also stated, "As concerns for a cleaner

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