Speculative tectonic model for the early Mesozoic arc of the southwest Cordilleran United States

Cathy J. Busby-Spera
Department of Geological Sciences, University of California, Santa Barbara, California 93106

ABSTRACT
The early Mesozoic continental arc of Arizona, California, and western Nevada is here interpreted to have occupied a continuous graben depression, more than 1000 km long, similar to the modern extensional arc of Central America. High calculated rates of subsidence, the presence of syn-depositional normal faults and fault-talus breccias, the abundance of calderas and high-level intrusions, and interstratification of calc-alkaline and alkaline volcanic rocks provide support for this model. The arc graben depression acted as a long-lived (more than 40 m.y.) trap for craton-derived quartz sands, which were funneled along the length and across the width of the depression.

INTRODUCTION
The term “Andean-type arc” has been applied to the Mesozoic volcanic-plutonic arc of California and Arizona because this arc formed on continental crust (Hamilton, 1969; Burchfiel and Davis, 1972). This analogy has led to the notion that this arc formed a high-standing region of uplift. Although there is evidence for uplift and erosion of the arc in late Mesozoic time (Dickinson and Rich, 1972; Fiske and Tobisch, 1978), a growing body of evidence indicates that subsidence was important along much of the arc in early Mesozoic time.

I speculate that the Late Triassic–Early Jurassic arc of Arizona, California, and western Nevada bore many similarities to the present-day arc of Central America (Fig. 1). Nearly all the arc volcanoes in Central America are within deep, fault-bounded depressions that owe their origin to extension and transtension along the trailing edge of the Caribbean plate (Burkart and Self, 1985). “Ganben syncline” structures control the site of strato-volcanoes and large calderas in the Kamchatka arc as well (Erlich, 1979). Whereas these modern analogues provide a “snapshot” of surficial features in extensional arcs, the early Mesozoic arc of the southwest Cordillera provides a three-dimensional view of an extensional or transtensional arc as it evolved over 40 m.y.

EVIDENCE FOR AN ARC GRABEN DEPRESSION
The origin of intra-arc basins, with extremely complex and episodic patterns of subsidence, sedimentation, and volcanism, is in general poorly understood. Structural depressions or troughs coincident with a volcanic-plutonic arc have been attributed to a variety of mechanisms. These include extension across the arc, transtension along intra-arc strike-slip fault zones, gravitational spreading above domes created by voluminous plutonism, faulting of the upper plate in response to segmentation of the subducting slab, and broad downwarps created by loss of eruptive products to atmospheric transport (Burbank and Self, 1985; Carr, 1976; Cole, 1984; Dalmayrac and Molnar, 1981; Erlich, 1979; Fitch, 1972; Hidebrand and Bowring, 1984; McBurney and Williams, 1965; Tobisch et al., 1986; Smith et al., 1987). Several lines of evidence, when considered together, suggest that the early Mesozoic arc of the southwestern United States occupied an extensional or transtensional graben depression (see Fig. 2), including (1) extreme thickening of Upper Triassic to Middle Jurassic continental and shallow-marine successions along the arc, relative to the adjacent craton, requiring high subsidence rates for their accumulation and preservation; (2) dispersal of quartz arenites across the width and along the length of the arc, suggesting that it acted as a funnel and a trap for craton-derived detritus; (3) abundance of high-level intrusions and thick ignimbrite sequences, and relative dearth of

Figure 1. Modern arc graben depression of Central America (from Burkart and Self, 1985; Dengo et al., 1970) and speculative model for southwest United States Cordillera in Late Triassic to early Middle Jurassic time. If an arc graben depression of dimensions of that in Central America is drawn on a map of southwestern United States, it encompasses nearly all thick intra-arc successions of early Mesozoic age; it is not clear, however, if proposed depression was as continuous as modern analogue at any one time, and its position could have shifted somewhat with time. Sections discussed in text (Figs. 3, 4, and 5) are plotted in Figure 1A. Inferred sediment dispersal in Wyoming, Utah, Arizona, and Nevada taken from Kocurek and Dott (1983); inferred sediment dispersal within arc is speculative. Large arrows in Figure 1B indicate plate-motion vectors. Calderas and volcanoes in Figure 1A are schematic.
mesozonal intrusions despite present-day exposures at a variety of crustal levels, suggesting that most magmas rose easily to upper crustal levels and erupted into volcano-tectonic depressions similar to those in modern extensional/transient environments (e.g., Sumatra, New Zealand); (4) presence of alkaline volcanic rocks locally interstratified with calc-alkaline volcanic rocks, similar to modern rifted arcs like the Colima graben, Mexico (Allan et al., 1988); (5) stratigraphic and structural evidence for syndepositional normal faults, including localized, thick sequences of polythiololc breccia that suggest faulting contemporaneous with sedimentation; and (6) occurrences of limestone and calc-silicate rocks interstratified with continental arc deposits, suggesting depressions occupied by marine embayments and/or large lakes.

Previous workers have suggested that subsidence rates in the early Mesozoic continental arc were high; furthermore, the distribution of craton-derived quartz sands across the width and along the length of the arc argues against its origin as a continuous high-standing feature (Miller, 1978; Busby-Spera, 1984a; Karish et al., 1987). Earlier workers correlated all intra-arc quartz arenites with the upper Pleischnachian to Toarcian Navajo Sandstone (Stanley et al., 1971; Bilodeau and Keith, 1986; Marzolf, 1982). New age data, however, show that these intra-arc quartz arenites vary in age by at least 40 m.y. (Wright et al., 1981; Riggs et al., 1986; Busby-Spera et al., 1987; Asmerom et al., 1988).

An arc graben depression could have acted as a long-lived trap for craton-derived quartz sands. These sands may have been funneled along the length of the depression, even if they only impinged upon a short segment of it (Fig. 1). Thus, the entire length of the arc graben depression could have been continuously fed quartz sands from once-extensive dune fields not preserved on the craton, as well as by less extensive coastal dunes that characterized periods of marine transgression on the craton (e.g., dune deposits at the southern margin of the Bajocian-Bathonian Carmel seaway). Additional sources of quartz sand could include recently deposited layers eroded from fault scarps (see recycling of quartz sand, Fig. 2).

A brief review, by geographic region, of published and new data that support my speculative model is given below.

Southern Arizona

Jurassic supracrystal rocks crop out extensively in this region (Reynolds, 1988). Quartz arenites interstratified with volcanic rocks in six ranges have all been correlated with the Lower Jurassic Navajo Sandstone by Bilodeau and Keith (1986). This interpretation is supported in the Baboquivari Mountains and Sil Nakya Hills by an upper intercept U-Pb zircon age of 190 Ma on metavolcanic rocks interstratified with quartz arenites (Wright et al., 1981). U-Pb zircon ages from the Santa Rita Mountains, however, suggest that some of these quartz arenites are older (205–210 Ma), perhaps Wingate-equivalent in age (Riggs et al., 1986; Asmerom et al., 1988).

Several features of the Fresnal Canyon sequence in the Baboquivari Mountains (Fig. 3A) suggest that it accumulated in an extensional arc setting (Haxel et al., 1985; Tosdal et al., 1988). U-Pb zircon dates from the bottom and top of

---

Figure 2. Speculative tectonic model for Late Triassic through Middle Jurassic arc of Arizona, California, and west-central Nevada.

Figure 3. Lithostratigraphic sections through Jurassic rocks of south-central Arizona. A: Baboquivari Mountains (Haxel et al., 1980; Tosdal et al., 1988). B: Cobre Ridge–Pajarito Mountains (Knight, 1970; Riggs, 1985; and unpub. data). C: Santa Rita Mountains (Drewes, 1971; Riggs and Busby-Spera, 1987; and unpub. data).
the section, and from a hypabyssal intrusion that cuts most of the section, indicate that this 8-km-thick section of continental volcanic and sedimentary rocks accumulated in less than 10 m.y. (Wright et al., 1981). High rates of subsidence are required to preserve such a thick continental succession. Minor alkaline mafic to silicic volcanic rocks interstratified with calc-alkaline ignimbrites provide evidence for extensional processes within the arc (Haxel et al., 1985). The 2.0-km-thick Pitoikam Formation contains a thick succession of angular to subangular polymict breccia that I interpret as fault talus breccia reworked by debris flows. Geochemical data on marbles and Mn-bearing metasedimentary rocks in the southern Bacoquivari Mountains (not shown in Fig. 3A) suggest that a marine environment may have existed for part of the Early Jurassic Period (Goodwin, 1985). This is shown as a marine embayment in Figure 1A, similar to modern-day embayments in Central America.

The Cobre Ridge tuff (Fig. 3B) is a 4.5-km-thick section of silicic ignimbrites and associated shallow-level intrusions, with locally interstratified quartz arenites, that occurs in the Pajarito Mountains and along Cobre Ridge in Arizona and Mexico. Work in progress and published data suggest that this may represent an Early or Middle Jurassic caldera complex (Riggs, 1987; Riggs and Busby-Spera, 1987).

Geochronological work on the Mount Wrightson Formation of the Santa Rita Mountains (Riggs et al., 1986; Asmerom et al., 1988) suggest that this 4-km-thick continental succession accumulated in a relatively short time; thus, high subsidence rates are required for its preservation. The Mount Wrightson Formation records the evolution of a multivert stratovolcano complex from an early effusive stage to a late explosive stage followed by waning volcanism (Fig. 3C). Rapid intra-arc subsidence resulted in burial of active vents by ignimbrites and reworked tuffs derived from other vents in the complex (Riggs and Busby-Spera, unpublished data). The Sawmill Canyon discontinuity, a northwest-trending regional lineament that bounds the Mount Wrightson Formation to the northwest, has been postulated to show hundreds of meters of normal slip (down to the southwest) between Perman and Middle Jurassic time (Titley, 1976). I speculate that this discontinuity, which marks the northern limit of thick Jurassic volcanic successions, formed the northeastern structural boundary of the arc graben depression in southern Arizona.

Southeast California–Southwest Arizona

Lower Mesozoic strata of this region can be divided into an older package correlative with Triassic strata of the Colorado Plateau, and a younger package consisting of collian quartz arenites overlain and intruded by silicic volcanic rocks (Fig. 4A). The silicic volcanic rocks, referred to as the Dome Rock sequence (Tosdal et al., 1988), have yielded a discordant Early or Middle Jurassic U-Pb zircon age at one locality in southeast Arizona (L. T. Silver, personal commun., in Crowl, 1979). The Dome Rock sequence is widely exposed in more than a dozen ranges and locally consists of ignimbrite sections up to 1 km thick that probably represent intracaldera accumulations (Tosdal et al., 1988).

Mojave Desert

Numerous workers have referred to quartz arenites, interstratified with volcanioclastic rocks in known or suspected early Mesozoic sections across the Mojave Desert, as "Aztec Sandstone," and have tentatively correlated this unit with the Lower Jurassic Navajo Sandstone (Hewett, 1931, 1956; Grose, 1959; Dunne, 1977; Miller and Carr, 1978; Marzolf, 1980). This interpretation has recently been called into question by new U-Pb zircon age data from the Cowhouse Mountains (Fig. 5A) which show that a lava flow within the Aztec Sandstone is 172 Ma, and the overlying Delfonte Volcanics are 167 Ma (Busby-Spera et al., 1987). The "Aztec Sandstone" in the Cowhouse Mountains may thus be age-equivalent to the Carmel Formation or possibly the Entrada Sandstone (using the DNAG geologic time scale; Palmer, 1983), and it is 20–30 m.y. younger than the quartz arenites in southern Arizona discussed above.

Several features taken together are suggestive of early Mesozoic intra-arc extension in the Mojave Desert region. Craton-derived quartz sand was distributed across the width of the arc, individual horizons reaching thicknesses of up to 700 m in the western Mojave (Fig. 4B) and 300 m in the eastern Mojave (unpub. data), suggesting that the arc occupied a low-lying region. Widespread, very thick ignimbrite sequences may represent intracaldera accumulations (see Sidewinder Volcanic Series, Fig. 4B). Mildly alkaline volcanic rocks are locally interstratified with calc-alkaline volcanic rocks (Fig. 5B; also see Karish et al., 1987). Marbles and metacalcareous silstones in the western Mojave (Fig. 4B; also in the Bean Canyon pendant, unpub. data) and in the eastern Mojave (Cowhouse Mountains, unpub. data) may indicate flooding of an arc graben depression by marine embayments or lakes. Evidence for syndepositional faults is sparse, but polymict breccia at the base of the Aztec Sandstone (Fig. 5A) may represent talus shed from such faults.

Sierra Nevada and West-Central Nevada

Upper Triassic through Lower Jurassic sequences in the Mineral King and Ritter Range pendants of the High Sierra represent the northern extension of the arc graben depression into the marine realm (Fig. 1). Triassic through Lower Jurassic volcanic and sedimentary rocks of the Yerington region may owe their marine character to broad subsidence in the Sonoma successor basin (northwest Nevada marine province of Speed, 1978) rather than to intra-arc

Figure 4. Selected early Mesozoic intra-arc lithostratigraphic sections of California plotted against DNAG geologic time scale (Palmer, 1983; lithologic symbols as in Fig. 3). A: Composite, generalized section along California-Arizona border (after Tosdal et al., 1988). B: Selected ranges in west-central Mojave (after Miller, 1978; Miller and Carr, 1978; Karish et al., 1987). C: Mineral King roof pendant of southern High Sierra (Busby-Spera, 1984a, 1984b; Busby-Spera and Saleeby, 1987). Rectangles show fossil ages; ovals show U-Pb zircon ages.

GEOLoGY, December 1988 1123
subidence, although a combination of the two subidence mechanisms is possible. By Middle Jurassic time, however, the marine province was lifted above sea level and the Yerington region was undergoing intra-arc extension and subsidence (Dilles and Wright, 1988).

Several features of the Mineral King section of the southern Sierra Nevada suggest that it was deposited in an arc graben depression: (1) high rates of subsidence of at least 200 m/m.y. are required to accumulate at least 6 km of shallow-marine sediment in less than 25 m.y. (calculated from upper half of section, Fig. 4C); (2) synsedimentary normal faults and associated fault talus breccias are present near the base of the Mineral King section; (3) four large-volume, caldera-forming eruptions are recorded in the section (Busby-Spera, 1984b); and (4) locally derived volcaniclastic rocks are present throughout the section, but quartz arenites that conformably overlie an ignimbrite dated at 190 Ma (Busby-Spera and Saleeby, 1987) may indicate that Navajo-equivalent sands gained access to the marine segment of the arc graben depression.

North of Mineral King, in the region of the Saddlebag Lake and Ritter Range pendants, a 10-km-thick section of silicic pyroclastic rocks accumulated in a shallow-marine environment in Late Triassic to Early Jurassic time. This indicates high intra-arc subsidence rates (Fiske and Tobisch, 1978) similar to those estimated for the Mineral King section (Busby-Spera, 1984a).

High rates of subsidence are required to accumulate and preserve the 4-km-thick section of continental strata that accumulated in less than 4 m.y. in the Yerington region (Dilles and Wright, 1988). This subsidence occurred within a graben bounded by syndepositional normal faults that downdropped the 169 Ma Yerington batholith and were cut by 165 Ma dikes. The volcanic rocks show a transitional calc-alkaline to mildly alkaline chemistry (Dilles and Wright, 1988) suggestive of intra-arc extension.

**CONCLUSIONS**

I suggest that continuous or semicontinuous belts of thick continental-arc sequences originate largely in extensional settings similar to the modern-day Central American arc graben depression. The early Mesozoic arc of the southwest United States provides an opportunity to document patterns of faulting, subsidence, and magmatism in three dimensions through approximately 40 m.y. of intra-arc extension. These results can then be applied to interpretation of more disrupted or metamorphosed continental arc successions of all ages.

The inference that crater-derived quartz sands gained access to the continental arc not once but many times over a period of at least 40 m.y. has important implications for terrane analysis. Rather than acting as a barrier, the rapidly subsiding arc received quartz sands across its width, and even beyond to the forearc region (Saleeby et al., 1989). Most of the forearc region, and possibly part of the arc, may have been subsequently removed by tectonic processes, probably including strike-slip faulting, but the approximate site of origin of these terranes may be inferred if quartz arenites are recognized within them.

**REFERENCES CITED**


Dengo, G., Bohlenberger, O., and Bonis, S., 1970, Tectonics and volcanism along the Pacific mar-

---

Figure 5. Aztec Sandstone and intercalated strata in eastern Mojave Desert near Baker, California (lithologic symbols as in Fig. 3). A: Composite section from Old Dad and Cowhole mountains (Dunne, 1977; Marzolf, 1983; and unpublished data). B: Highway Spur measured section, Soda Mountains (unpub. data).


Fitch, T.J., 1972, Plate convergence, transcurrent faults, and internal deformation adjacent to Southeast Asia and the western Pacific: Journal of Geophysical Research, v. 77, p. 4432–4460.


Hillebrand, R., and Bowring, S., 1984, Continental intra-arc depressions: A non-extensional model for their origin, with a Proterozoic example from Wyoming: Geology, v. 12, p. 73–77.


ACKNOWLEDGMENTS

Supported by National Science Foundation Grant EAR-8519124. I thank W. Dickinson, G. Davis, E. Miller, N. Riggs, G. Smith, and R. Tosdal for reviews of the manuscript, and G. Haxel, J. Mattinson, and J. Wright for helpful discussions. U-Pb zircon analyses were performed by James Mattinson.

Reviewer’s comments

One of the most thoughtful and potentially useful fresh ideas on Cordilleran geology to emerge in the last decade.

William R. Dickinson