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Refining the Early History of the Mojave-Yavapai Boundary Zone: Rifting versus Arc Accretion as Mechanisms for Paleoproterozoic Crustal Growth in Southwestern Laurentia

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ABSTRACT

Three outstanding questions regarding Paleoproterozoic crustal growth and assembly in southwestern Laurentia are (1) the mechanisms of crustal growth (back-arc rifting and associated juvenile magmatism vs. accretion of juvenile arcs), (2) the nature and significance of pre-Yavapai orogeny (>1.70 Ga) deformation, and (3) how the isotopically mixed boundary zone between the Mojave and Yavapai Paleoproterozoic crustal provinces formed. Supracrustal successions associated with the Mojave-Yavapai boundary zone in northwestern Arizona are dominated by >1730 Ma bimodal metavolcanic sequences and compositionally siliciclastic metasedimentary rocks, with minor ultramafic rocks, chert, and carbonate. This lithologic assemblage requires juvenile mafic volcanism in a basin that also received abundant quartz-rich (i.e., continental) detritus. A pre-D_1 (first deformational event), back-arc rift setting for northwestern Arizona best explains the observed supracrustal assemblage. Plutonic rocks that intrude the supracrustal rocks are generally 5–15 m.yr. younger and span the entire compositional range of granitoids; i.e., they are not plutonic equivalents of the metavolcanic rocks. In the model presented here, supracrustal rocks were deposited in a back-arc basin above an east-dipping subduction zone undergoing slab rollback. Subsequent shallowing of the subducting slab resulted in (1) eastward migration of 1.76–1.74 Ga arc magmatism in eastern California to 1.73–1.71 Ga arc magmatism within the former back-arc basin in northwestern Arizona, (2) consequent closure of the back-arc basin, (3) thrusting of Yavapai province rocks over the basin (D_1), resulting in (4) burial of supracrustal rocks to >20 km, and ultimately, (5) gravitational collapse of the orogen. These events predated the 1.70–1.68 Ga Yavapai orogeny and occurred within a time interval of 5–20 m.yr. Similar time intervals for tectonic switching have been documented from the Lachlan orogen of eastern Australia. Rifting and associated magmatism and arc accretion are both viable—and not mutually exclusive—mechanisms for crustal growth.

Introduction

Differing mechanisms of crustal growth leave behind signatures that permit them to be distinguished in the rock record (e.g., lateral accretion of primitive arcs, arc magmatism, magmatic underplating, magmatic additions in rift zones). In the southwestern United States, the complex boundary zone between the Mojave and Yavapai crustal provinces (fig. 1) must represent a composite of several mechanisms. Characteristics of this boundary zone that are important clues to the mechanisms of crustal growth—and that must be accounted for in any tectonic model—include a wide (~75 km) isotopically mixed zone of juvenile and evolved crustal materials; bimodal volcanism; felsic, intermediate, and mafic plutonism; large volumes of quartz-rich metasedimentary rocks; polyphase deformation; granulite-grade metamorphism; and gravitational collapse of overthickened crust. This article focuses on the early, pre-Yavapai orogeny (1.70–1.68 Ga) tectonic setting of the enigmatic Mojave-Yavapai boundary zone.

The period between 1.78 and 1.63 Ga was one of major crustal growth in the western United States. During this time interval, a 1300-km-wide band of crust was added along the southern margin of Laurentia (e.g., Hoffman 1988; Whitmeyer and Karlstrom

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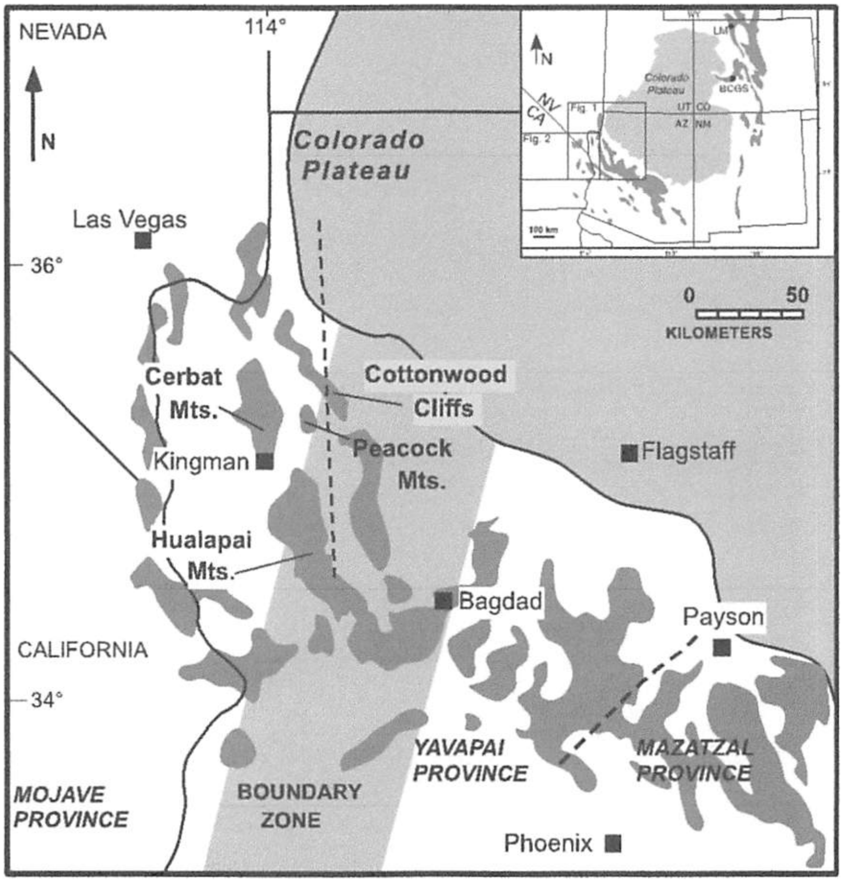

Figure 1. Index map of Arizona and adjacent areas showing distribution of Proterozoic crustal provinces and the Mojave-Yavapai boundary zone. The boundary zone after Wooden and DeWitt (1991) is shaded. The northeast-trending dashed line is the approximate boundary between Yavapai and Mazatzal provinces. The north-trending dashed line is the western margin of the Mojave-Yavapai boundary zone of Duebendorfer et al. (2006). *Inset*, BCGS = Black Canyon–Gunnison-Salida area, LM = Lester Mountain.

2007). The nature of this material—be it evolved continental, juvenile, transitional, or composite and how it was added to the southern margin of Laurentia—has been the subject of considerable controversy (e.g., Hill and Bickford 2001; Bickford and Hill 2007; Karlstrom et al. 2007; Whitmeyer and Karlstrom 2007). Two end-member models have been proposed for crustal growth during the protracted Paleoproterozoic orogeny: the arc-accretion model and a model that invokes rifting of older crust (rift-accretion model). In the prevailing arc-accretion model (Karlstrom and Bowring 1988, 1993; Jessup et al. 2005; Karlstrom et al. 2007; Whitmeyer and Karlstrom 2007), most of this material is considered to be mantle-derived juvenile crust that formed outboard and subsequently accreted, and therefore represents, newly formed crust (at 1.78–1.65 Ga); but the model does not preclude the presence of some fragments of older continental crust (Jessup et al. 2005; Whitmeyer and Karlstrom 2007; Karlstrom and Williams 2012). In one rift-accretion model, Penokean and older crust is inferred to underlie much of the southwestern United States on the basis of Sm-Nd isotopic data, the occurrence of abundant 1850 Ma and 2500 Ma inherited zircons as cores and xenocrysts (Hill and Bickford 2001; Hill 2004; Bickford and Hill 2007), and limited zircon Hf isotopic studies (Bickford et al. 2008). Similarly, J. V. Jones et al. (2009) and D. S. Jones et al. (2010) presented rift-accretion models (discussed below) for the southern and northern parts, respectively, of the Paleoproterozoic orogen in southwestern Laurentia. In all of these models, rifting of continental or oceanic crust and attendant bimodal magmatism contributed to crustal growth.

In this article, I propose a tectonic model that incorporates elements of both models to explain crustal growth within, and the formation of, the Mojave-Yavapai boundary zone in northwestern Arizona. Although the proposed model is specific to the Mojave-Yavapai boundary zone, elements of it may be relevant to other areas in the Paleoproterozoic orogen of southwestern Laurentia.

Background

Three distinct Paleoproterozoic crustal provinces—the Mojave, the Yavapai, and the Mazatzal (fig. 1)—have been identified in the southwestern United States on the basis of Nd and Pb isotopic and geochronologic data (Nelson and DePaolo 1985; Bennett and DePaolo 1987; Wooden et al. 1988). At the surface, the southernmost extent of Yavapai crust appears to coincide with the northeast-trending Jemez lineament that extends from eastern Arizona to northeastern New Mexico (Karlstrom and Humphreys 1998; Shaw and Karlstrom 1999), although at depth, the boundary has been interpreted as a 170-km-wide bivergent suture zone (Magnani et al. 2004). The Mojave-Yavapai boundary has been described as a diffuse >75-km-wide zone with Pb isotopic characteristics intermediate between those of the two provinces (fig. 1; Wooden and DeWitt 1991). Wooden and DeWitt (1991, p. 35) used a normalization technique, based on Pb isotopic data on galena from the United Verde Mine at Jerome, Arizona, to emphasize differences in $^{207}Pb/^{204}Pb$ between samples. They defined a dimensionless parameter, which they term Delta Jerome (ΔJ), to simplify discussion and comparison of Pb isotopic ratios between provinces. Values for Mojave crust are $\Delta J > 6$; for Yavapai, they are $\Delta J < 2$.

Mojave Province. The Mojave crustal province was first defined on the basis of Nd ($T_{DM} = 2.3$ to 2.0 Ga; $\varepsilon_{Nd} = -4.5$ to $+0.28$; Bennett and DePaolo 1987) and Pb isotopic characteristics (Wooden and Aleinikoff 1987; Wooden et al. 1988). These studies showed that Mojave crust is more isotopically evolved than the juvenile Yavapai crust to the east and required some contribution from an Archean source (Rämö and Calzia 1998). Later Pb and Hf isotopic and geochronologic studies (Chamberlain and Bowring 1990; Wooden and Miller 1990; Wooden and DeWitt 1991; Wooden et al. 2012) confirmed the widespread presence of a pre-1800 Ma crustal component in the Mojave. Limited U-Pb dating of detrital zircons in metasedimentary rocks and inherited zircons in granitoids show that material as old as 3.3 Ga was involved in the formation of Mojave crust (Wooden et al. 2012), but this does not require Archean crust at depth. On the basis of evolved Pb, Nd, and Hf isotope signatures as well as Archean detrital and xenocrystic zircons, however, some authors (Whitmeyer and Karlstrom 2007; Shufeldt et al. 2010; Karlstrom and Williams 2012; Holland et al. 2013) have suggested the possible presence of Archean crustal blocks in the subsurface.

The Mojave province has been divided into a western subprovince that comprises the San Bernardino, Lost Horse, Pinto, and Eagle Mountains and an eastern part that includes the Ivanpah, New York, and Old Woman-Piute Mountains in California and the Cerbat, Peacock, and Hualapai Mountains and parts of the Grand Wash Cliffs in northwestern Arizona (fig. 2; Wooden and DeWitt 1991; Barth et al. 2009). In this article, the eastern Mojave province is further divided into a California Mojave subprovince and an Arizona Mojave subprovince due to temporal differences in magmatism.

The oldest dated rock in the western Mojave province is the Baldwin Lake orthogneiss in the San Bernardino Mountains (1783 ± 12 Ma; U-Pb zircon) that intrudes amphibolites and psammitic metasedimentary rocks (Barth et al. 2000). In the California Mojave subprovince, the oldest dated orthogneisses range in age from 1766 to 1759 Ma (Barth et al. 2009), and these rocks intrude a lithologically heterogeneous suite of migmatites, mafic gneiss, garnet-sillimanite-biotite gneiss, amphibolite, pelitic gneiss, and rare ultramafic and quartz-rich rocks (e.g., Wooden and Miller 1990; Anderson et al. 1993).

The oldest reliably dated granitoids in the Arizona Mojave subprovince are ca. 1735 Ma, and these intrude >1735 Ma amphibolite; bimodal metavolcanic rocks; compositionally immature quartzite (psammite); migmatitic garnet-biotite gneiss; and minor calc-silicate gneiss, ultramafic rocks, and metachert (Duebendorfer et al. 2001). It should be noted that although the 1840 ± 1 Ma Elves Chasm orthogneiss of the Upper Granite Gorge in Grand Canyon has Pb isotopic signatures characteristic of the Mojave province (Hawkins et al. 1996), it lies within the isotopically mixed Mojave/Yavapai boundary zone (i.e., there are rocks with Yavapai-like Pb signatures to the west in the Grand Wash Cliffs). The Elves Chasm orthogneiss has been interpreted as basement on which the 1750 ± 2 Ma Vishnu Schist was deposited (Hawkins et al. 1996), and its discovery, along with the SHRIMP U-Pb ages of inherited zircons in central Colorado, led

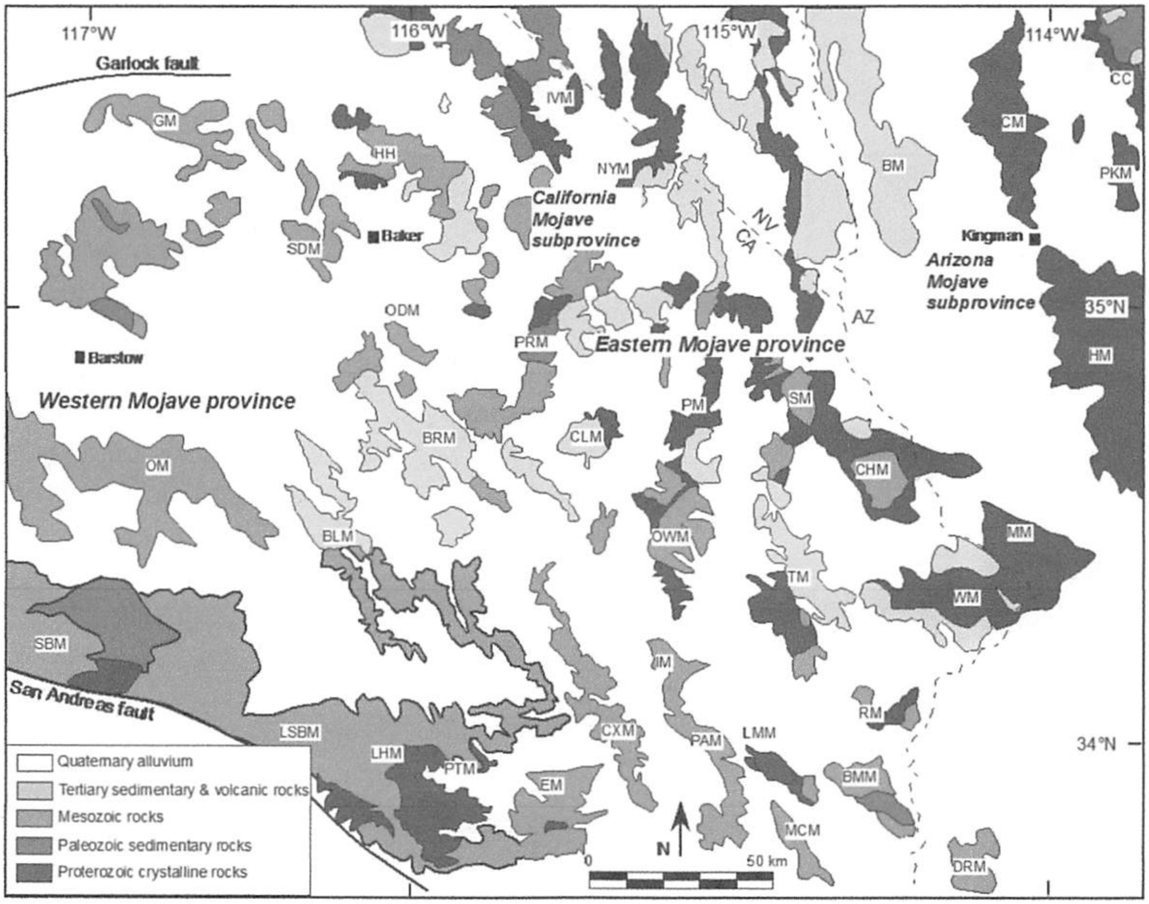

Figure 2. Map of Mojave Desert showing eastern and western Mojave province and the California and Arizona subprovinces. Area of figure 2 is outlined in the inset (upper right corner) of figure 1. Mountain ranges: BLM = Bullion Mountains, BM = Black Mountains, BMM = Big Maria Mountains, BRM = Bristol Mountains, CC = Cottonwood Cliffs, CHM = Chemehuevi Mountains, CLM = Clipper Mountains, CM = Cerbat Mountains, CXM = Coxcomb Mountains, DRM = Dome Rock Mountains, EM = Eagle Mountains, GM = Granite Mountains, HH = Halloran Hills, HM = Hualapai Mountains, IM = Iron Mountains, IVM = Ivanpah Mountains, LHM = Lost Horse Mountains, LMM = Little Maria Mountains, LSBM = Little San Bernardino Mountains, MCM = McCoy Mountains, MM = Mohave Mountains, NYM = New York Mountains, ODM = Old Dad Mountains, OM = Ord Mountains, OWM = Old Woman Mountains, PAM = Palen Mountains, PKM = Peacock Mountains, PM = Piute Mountains, PRM = Providence Mountains, PTM = Pinto Mountains, RM = Riverside Mountains, SBM = San Bernardino Mountains, SDM = Soda Mountains, SM = Sacramento Mountains, TM = Turtle Mountains, WM = Whipple Mountains.

Hill and Bickford (2001) to propose that Trans-Hudson-Penokean crust (1870–1820 Ma) may underlie much of the southwestern United States.

Within the California Mojave subprovince, there is a gap in magmatism between 1.73 and 1.69 Ga with an older, arc-related suite (1.79–1.73 Ga) dominated by tonalite, trondhjemite, and granodiorite and a younger (1.69–1.64 Ga) suite that consists largely of high-K granitic rocks (Wooden et al. 2000; Coleman et al. 2003; Barth et al. 2009). In the Arizona Mojave subprovince, pre-Yavapai (>1.71 Ga) plutonic rocks comprise the entire spectrum of compositions (mafic-intermediate-felsic) and generally range in age from 1.735 to 1.71 Ga (Duebendorfer et al. 2001), which coincides temporally with the magmatic gap farther west. The significance of this observation is discussed below.

Yavapai Province of Arizona. Nd (T_{DM} = 2.0 to 1.8 Ga; ε_{Nd} = +0.62 to 4.73) and lead isotopic data suggest that the Yavapai province in Arizona is composed of juvenile additions to the crust with little contribution of pre-1800 Ma crust (Bennett and DePaolo 1987; Wooden and DeWitt 1991). The Gunnison area in central Colorado (fig. 1, *inset*) shows isotopic or inherited zircon evidence for presence of an older crustal component (Hill and Bickford 2001; Bickford et al. 2008); however, according to Whitmeyer and Karlstrom (2007), the Nd model ages, which for the most part are within 10–100 m.yr. of U-Pb crystallization ages (Bennett and DePaolo 1987), preclude large volumes of older material.

Nevertheless, there is indirect evidence that older crust may be present within the Yavapai province and the Mojave-Yavapai boundary zone. Shufeldt et al. (2010) obtained 1035 detrital zircon ages from 12 spatially distributed samples of the 1750 ± 2 Ma Vishnu Schist that included five samples from east of the Crystal shear zone, a structure that marks the eastern margin of the Mojave-Yavapai boundary zone (Hawkins et al. 1996). These samples, clearly within the Yavapai province, yielded two distinct peaks, one at 2480 Ma and another at 1862–1814 Ma. The latter ages overlap with the 1840 ± 1 Ma Elves Chasm orthogneiss. A surprising 30% of detrital zircons from the entire data set yielded Archean ages of 3.8–2.5 Ga. Although Shufeldt et al. (2010) acknowledge that the zircons could have been derived from "cratons and blocks that may have been adjacent to southwestern Laurentia" (p. 1101; e.g., Gawler Craton of Australia, South China Craton, North China Craton, East Antarctic Craton), their preferred interpretation, based on the large percentage of Archean detrital zircons, is that there is Archean crust in the middle and lower crusts of the Mojave province (possible source area for the Vishnu Schist) and possibly the Yavapai province. This interpretation is supported by the presence of three (of eight) xenocrystic zircon fractions from the Tuna Creek (Upper Granite Gorge, Grand Canyon) pluton that yielded $^{207}Pb/^{206}Pb$ ages between 1946 and 2178 Ma (Hawkins et al. 1996), suggesting that the granodioritic magma may have sampled older crust during the generation and ascent of the arc magma.

The Yavapai province of Arizona comprises a series of tectonic blocks that were juxtaposed along ductile shear zones by 1690 Ma (Karlstrom and Bowring 1988, 1993). Supracrustal sequences in the province consist of 1.76–1.73 Ma metavolcanic rocks of all compositions, volcanogenic metasedimentary rocks, and subordinate pelitic and psammitic rocks (e.g., Karlstrom et al. 1987 and references therein). A diverse suite of arc granitoids ranging in age from 1750 to 1690 Ma intrudes these rocks (Karlstrom and Bowring 1988, 1993; Hawkins et al. 1996).

The Mojave-Yavapai Boundary Zone. Wooden and DeWitt (1991) identified a >75-km-wide, north-northeast-trending zone in northwestern Arizona that has Pb isotopic signatures intermediate between those of the Mojave and Yavapai crustal provinces (fig. 1, "boundary zone"). The Pb isotope map of Wooden and DeWitt (1991; fig. 3) shows that Pb isotope values within the Mojave-Yavapai boundary zone vary widely between values representative of the Mojave and Yavapai provinces and show no systematic relation to position within the boundary zone. Intriguingly, the Pb isotopic boundary zone of Wooden and DeWitt (1991) trends north-northeast, at a high angle to both regional D_1 and D_2 Proterozoic fabrics.

The eastern margin of the Mojave-Yavapai boundary zone as defined by Wooden and DeWitt (1991) appears to be the Crystal shear zone exposed in the Upper Granite Gorge of the Grand Canyon (Hawkins et al. 1996; Ilg et al. 1996). Across this structure, Yavapai-type crust grades into Mojave-type crust in <5 km. West and south, however, are several domains of isotopically juvenile rocks that correspond to exposures of bimodal metavolcanic sequences in

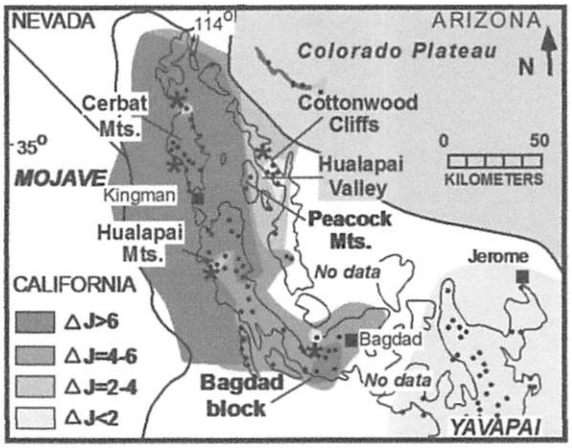

Figure 3. Map of northwestern Arizona showing distribution of Pb isotopic data, contoured in Delta Jerome (ΔJ) units after Wooden and DeWitt (1991). Values of ΔJ > 6 are typical of Mojave crust; values of ΔJ < 2 are typical of Yavapai crust. Note the sharp north-trending gradient in Pb isotopic values between the Cottonwood Cliffs and Peacock Mountains, and compare its location with the geochemical and metamorphic discontinuities in figure 4. Black circles show sample localities of Wooden and DeWitt (1991) and Chamberlain (unpubl. data). Asterisks show locations of pillow basalts. Area of figure 3 is in the central part of figure 1. Note locations of Kingman, Bagdad, and several mountain ranges on both figures for reference.

the Cottonwood Cliffs and the Hualapai Mountains (herein referred to as a trough in Pb isotope values). An "island" of Mojave-type crust near Bagdad, Arizona (fig. 3, "Bagdad block"), is exposed between primitive Yavapai crust to the east and isotopically mixed crust to the west.

The western margin of the Mojave-Yavapai boundary zone has been interpreted to be the northeast-striking Gneiss Canyon shear zone exposed in the Lower Granite Gorge of the Grand Canyon (e.g., Karlstrom and Morgan 1988); however, the southwestern projection of this structure crosscuts the major Pb isotopic contrast in northwestern Arizona (figs. 1, 3). More recently, Duebendorfer et al. (2006) proposed that the western margin of the boundary zone is coincident with north-trending isotopic, geochemical, metamorphic, and geophysical discontinuities between the Cottonwood Cliffs and the Peacock Mountains (fig. 4).

Deformation

The Mojave and Yavapai provinces in Arizona share evidence for at least two distinct, pre-Mazatzal orogeny (ca. 1.65–1.63 Ga) deformational events. The early event, D_1, produced map-scale and mesoscopic recumbent folds. The axial planar foliation associated with these folds dips gently moderately east to northeast, consistent with fold vergence to the west or southwest. West-vergent recumbent folds associated with D_1 have been recognized in central Arizona (O'Hara et al. 1978; Karlstrom and Bowring 1988; Bergh and Karlstrom 1992), and macroscopic and mesoscopic recumbent folds and nappes of unknown vergence have also been documented in the Upper Granite Gorge of the Grand Canyon (Ilg et al. 1996). Event D_1 has been bracketed between 1.74 and 1.72 Ga in the Cerbat Mountains (Duebendorfer et al. 2001), between 1.73 and 1.715 Ma in the upper Granite Gorge of the Grand Canyon (Hawkins et al. 1996; Ilg et al. 1996), and between 1.74 and 1.73 Ga in the central Arizona Yavapai province (Karlstrom and Bowring 1991; Bergh and Karlstrom 1992). The similarity in kinematics and age of D_1 deformation in the eastern Mojave and Yavapai provinces strongly suggests that they represent the same deformation event. Duebendorfer et al. (2001) proposed that D_1 structures formed as a result of a collision of the Yavapai arc with the eastern Mojave province sometime between 1.74 and 1.715 Ga.

Figure 4. Map of northwestern Arizona showing geochemical discontinuities and a sharp metamorphic boundary (granulite facies to west, greenschist facies to east) within 8-km distance. Xgr = Paleoproterozoic granites, CA = calc-alkaline, K = potassic, Ygr = Mesoproterozoic granites, PA = peraluminous, MA = metaluminous, Nd = Nd isotopic boundary from Bennett and DePaolo (1987). Geochemical boundaries from Anderson et al. (1993). Area is the same as in figure 1.

The second deformation, D_2, produced a subvertical, northeast-striking foliation; is constrained to 1700–1685 Ma (e.g., Karlstrom and Bowring 1988, 1993); and probably records the juxtaposition of a composite Mojave-Yavapai crustal block to Paleoproterozoic terranes in central Colorado (Duebendorfer et al. 2001). This event is referred to as the Yavapai orogeny in Arizona (Karlstrom and Bowring 1988) and the Ivanpah orogeny in eastern California (Wooden and Miller 1990).

Supracrustal Rocks

Figure 5 shows localities of supracrustal rocks in northwestern Arizona with the relative abundances of rock types listed in descending order. In the discussion below, rock types for each supracrustal sequence are listed in order of decreasing abundance.

Northern Cerbat Mountains. The dominant supracrustal rocks in this area are quartzofeldspathic gneiss, garnet-biotite (± sillimanite, cordierite, accessory phases) gneiss, amphibolite, and calc-silicate gneiss (Orr 1997). The quartzofeldspathic gneiss is interpreted to be a felsic metavolcanic rock (flows and/or tuffs) on the basis of the relatively high feldspar : quartz ratio and the presence of clino- and orthopyroxene, probable stretched amygdules, and euhedral, well-faceted zircons (Orr 1997). This sequence is intruded by a foliated granite that yielded

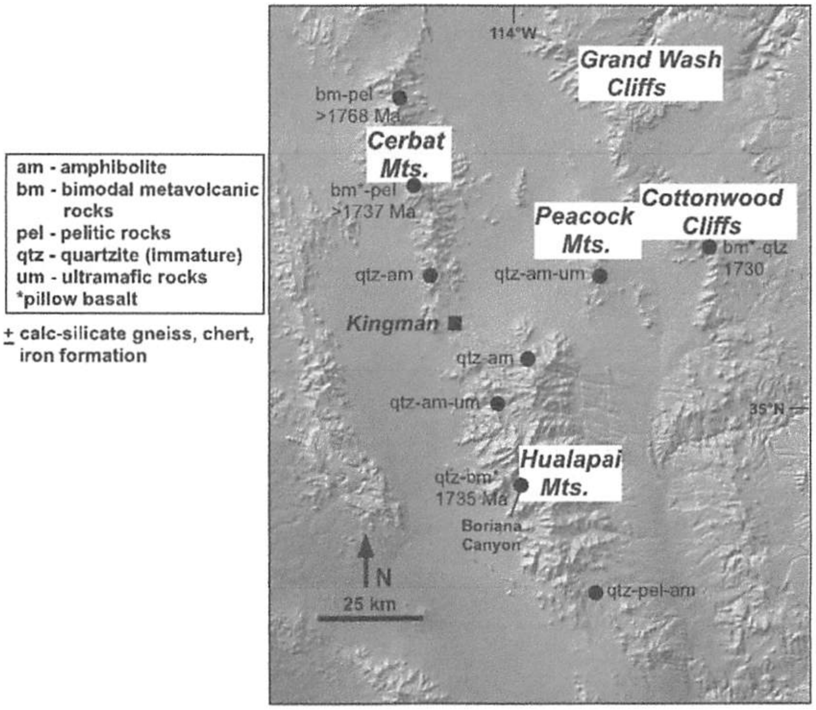

Figure 5. GeoMapApp (http://www.geomapapp.org) image of northwestern Arizona showing distribution of major supracrustal rocks in four ranges. Rock types are listed in order of decreasing abundance. For area of figure, compare locations of Kingman and several mountain ranges on figures 1 and 3. A color version of this figure is available online.

a U-Pb zircon date of 1768 ± 6 Ma (Duebendorfer et al. 2001). The association of the quartzofeldspathic gneiss with amphibolite suggests that this part of the supracrustal succession in the northern Cerbat Mountains represents a bimodal volcanic sequence. On the basis of mineralogy, the protolith of the garnet-biotite gneiss was a pelite. The calc-silicate gneiss is interpreted to have originated as an impure carbonate deposited in a shallow marine setting.

Central and Southern Cerbat Mountains. These areas are characterized by subequal amounts of amphibolite (metabasalt with relict pillows) and biotite quartzofeldspathic schist, with subordinate migmatitic garnet-biotite (± sillimanite, cordierite, accessory phases) gneiss, and metarhyolite. Other volumetrically minor rock types include ultramafic pods and lenses, metachert, and calc-silicate rocks. Metarhyolite was identified on the basis of quartz "eyes" (Williams and Burr 1994) that likely represent phenocrysts. The metabasalt : metarhyolite ratio, on the basis of surface exposure, is about 8 : 1, suggesting an oceanic versus continental tectonic setting, as rhyolites are uncommon in oceanic settings. The biotite quartzofeldspathic schist consists of, in descending order of abundance, quartz + plagioclase + K-feldspar + biotite ± garnet ± hornblende. Some samples contain >20% biotite. Biotite, garnet, and hornblende likely represent an original clay component. On the basis of mineralogy, the protolith of this unit is interpreted to be a compositionally immature quartzite. The abundance of feldspars suggests a relatively short transport distance of the sediment. The supracrustal rocks are cut by the Big Wash granite, which yielded a U-Pb zircon age of 1737 ± 4.3 Ma, and a 1736 ± 6 Ma dacite sill (Duebendorfer et al. 2001). These dates are interpreted as a minimum age of the metasedimentary/metavolcanic sequence. A ca. 1650 Ma sill from the eastern Cerbat Mountains yielded an inherited zircon with a U-Pb date of 2831.7 ± 1.2 Ma (Duebendorfer et al. 2001). Supracrustal rocks were metamorphosed to the granulite facies at 725°C and 650 MPa, on the basis of garnet-biotite and GASP thermobarometry (Duebendorfer et al. 2001).

Northern Hualapai Mountains. Biotite quartzofeldspathic schist dominates the supracrustal sequence in the northern Hualapai Mountains. The schist, composed of quartz + K-feldspar + plagioclase + biotite ± garnet, is mineralogically indistinguishable from schists in the southern Cerbat Mountains, and its protolith is interpreted to be a compositionally immature quartzite. Amphibolite is present as pods and lenses on the order of tens of meters in maximum dimension; however, a single discontinuous (boudinaged) exposure of fine-grained amphibolite, 3–4 km long, and more than 100 m wide, is intimately associated with the quartzofeldspathic schist (Siwiec 2003). It is not clear whether the protolith was extrusive or intrusive (i.e., part of the supracrustal sequence or not, respectively); however, its fine grain size favors the former interpretation. Volumetrically minor metapelitic rocks within the unit contain coexisting sillimanite and K-feldspar in the absence of prograde muscovite, indicating granulite-facies metamorphism. Quantitative thermobarometry yielded metamorphic temperatures of 720°C and pressures of 620 MPa (Siwiec 2003).

Central Hualapai Mountains. In the central Hualapai Mountains, two distinct sequences of supracrustal rocks are exposed that may be separated by an unconformity on the basis of differences in metamorphic grade. The inferred older rocks consist of amphibolite and felsic gneiss (2:1 ratio; Conway et al. 1990) that are interpreted to represent a bimodal volcanic sequence on the basis of mineralogy and relict volcanic textures (pillows, phenocrysts, volcaniclastic textures). A metarhyolite from the bimodal sequence yielded a U-Pb zircon date of 1735 ± 7 Ma (Chamberlain and Bowring 1990). Some of the amphibolites are spatially associated with syngenetic massive sulfide deposits that are interpreted as having formed during seafloor mineralization (Stensrud and More 1980; Conway et al. 1990). North of Boriana Canyon (fig. 5), these metavolcanic rocks interfinger with and become volumetrically subordinate to the biotite quartzofeldspathic schist of the northern Hualapai Mountains. The inferred younger sequence, exposed exclusively in the Boriana Canyon region, consists of alternating white quartzite (locally pebbly) and muscovite-biotite quartz schist. Protoliths of these units are interpreted to be sandstone and siltstone/shale, respectively. The more pelitic components of the schist contain garnet, staurolite, andalusite, and prograde muscovite, indicating metamorphism at the middle amphibolite facies, in contrast to the granulite-grade conditions recorded in the rocks in the northern and southern Hualapai Mountains. In fact, 5 km south of Boriana Canyon (fig. 5), a garnet-biotite schist contains sillimanite + K-feldspar ± hercynite in the absence of prograde muscovite. The biotite quartzofeldspathic schist in the northern Hualapai Mountains and the garnet-biotite schist 5 km south of Boriana Canyon are thus interpreted as the high-grade basement on which the white quartzite and muscovite-bearing quartz schist were deposited.

Southern Hualapai Mountains. The dominant lithology in this area is a heterogeneous sequence of biotite quartzofeldspathic schist and gneiss that has been extensively but not universally migmatized (Bonamici 2007; Portis 2009). Paleosomes of pelitic protoliths contain biotite + garnet + sillimanite + K-feldspar + plagioclase in the absence of prograde muscovite, indicating metamorphism at the granulite facies. Melanosomes contain the refractory phases garnet, biotite, and sillimanite, with the notable absence of quartz and feldspar; leucosomes contain quartz + K-feldspar + plagioclase ± garnet ± cordierite, indicating that migmatization occurred by partial melting of a pelitic protolith. Quantitative thermobarometry indicates temperatures of metamorphism at 800° ± 188°C and pressures of 920 + 300 MPa (Bonamici and Duebendorfer 2009). The protoliths of this unit are interpreted as siliciclastic sedimentary rocks, including compositionally immature sandstone, siltstone, and mudstone. Volumetrically minor but significant rock types include metapyroxenite (wehrlite) and amphibolite that appear to be the oldest rocks in the area. These represent metamorphosed ultramafic rocks and mafic rocks, respectively. There are no age constraints on the supracrustal rocks in the southern Hualapai Mountains.

Peacock Mountains. Psammitic schist consisting of quartz + K-feldspar + plagioclase + biotite ± garnet ± hornblende is the most abundant supracrustal rock type in the Peacock Mountains (Prante 2009). The protolith of the psammitic schist was likely compositionally immature sandstone, with locally interleaved pelitic schist representing siltstone and mudstone lenses. Intimately associated with these schists are fine-grained amphibolite and texturally variable hornblende gneiss. The amphibolite is composed of hornblende + clinopyroxene + plagioclase + minor accessory minerals and is interpreted as metamorphosed basalt. The hornblende gneiss is composed of hornblende + plagioclase ± K-feldspar ± clinopyroxene ± quartz ± biotite ± olivine ± titanite. The coexistence of mafic and felsic minerals in the gneiss suggests that its protolith was a volcanogenic sedimentary rock. The hornblende gneiss is interlayered on the centimeter scale with felsic gneiss that is interpreted as a felsic metavolcanic rock. Local lenses (tens of meters) of ultramafic rock are volumetrically minor but widely distributed components of the supracrustal succession in the Peacock Mountains. Quantitative thermobarometry indicates temperatures of metamorphism at 600°C and pressures of 540 MPa (Prante 2009). These are likely minimum estimates of temperature and pressure due to retrograde reequilibration between garnet and biotite, as indicated by granulite facies (sillimanite + K-feldspar) mineral assemblages in metapelites.

Cottonwood Cliffs. The Cottonwood Cliffs can be divided into three lithologically distinct blocks, two of which are overlain unconformably by a siliciclastic unit that includes boulder-cobble metaconglomerate (overlap sequence; Evans 1999). The westernmost block is dominated by amphibolite with lesser amounts of phyllite and schist. The amphibolite is interpreted as metamorphosed basaltic flows, agglomerates, and tuffs based on the presence of relict pillows and other volcanic textures (Beard and Lucchitta 1993). Chamberlain and Bowring (1990) suggest an age of 1730 Ma for the amphibolite on the basis of slightly discordant U-Pb zircon data from two analyzed fractions. The amphibolite is locally cut by metafelsite dikes, one of which yielded a U-Pb zircon date of 1727 ± 8 Ma (Chamberlain and Bowring 1990), providing an upper age limit for the supracrustal rocks. The central block contains a heterogeneous assemblage of greenschist-grade phyllite and schist that has been interpreted, on the basis of mineralogy and textural features, to represent siliciclastic and volcanogenic metasedimentary rocks and felsic volcanic rocks (Beard and Lucchitta 1993). Minor metachert is also present within the central block. The contact between the central and western blocks is buried beneath the overlap sequence; it could be either depositional or tectonic. The eastern block consists of quartz-rich, biotite-chlorite schist, and phyllite metamorphosed to the greenschist facies. The protoliths of these rocks were probably siltstone, compositionally immature sandstone, and felsic volcanic rocks (Evans 1999). A granodiorite that cuts these rocks yielded a U-Pb date of 1730 ± 9 Ma (Chamberlain and Bowring 1990). The overlap sequence is composed of metamorphosed conglomerate, orthoquartzite, siltstone, and minor claystone. The dominantly clast-supported metaconglomerate contains clasts of metamorphosed orthoquartzite (to 0.5 m across), metachert, schist, and phyllite. The latter rock types are interpreted to have been derived from the underlying central block (Evans 1999). The source area for the orthoquartzite clasts within the metaconglomerate is unknown.

Plutonic Rocks

Figure 6 shows the distribution, age, and rock type of all dated pre-1710 Ma granitoids in northwestern Arizona. This age cutoff was chosen to include only rocks that clearly predate the ca. 1700 Ma Yavapai-Ivanpah orogeny. With few exceptions, these granitoids range in age from 1735 to 1715 Ma. Two features are worthy of note: (1) in most cases, these granitoids are only slightly younger (5–15 m.yr.) than the supracrustal rocks that they intrude; and (2) plutonic rocks comprise the full compositional spectrum of intrusive rocks in contrast to the bimodal composition of the supracrustal metavolcanic rocks, with more than half of dated granitoids intermediate to mafic in composition (granodiorite, diorite, tonalite, gabbro). Intermediate rocks are rare in the supracrustal metavolcanic successions.

The compositions of the granitoids in northwestern Arizona are similar to older orthogneisses in the Ivanpah, Old Woman-Piute, and New York Mountains of eastern California that include tonalite, trondhjemite, granodiorite, and granite (Barth et al. 2009; Wooden et al. 2012) and that have been interpreted as arc rocks on the basis of calc-alkaline chemistry and low abundances of immobile high-field-strength elements (Flodin et al. 1997). These orthogneisses range in age from 1766 ± 12 to 1732 ± 19 Ma (Barth et al. 2009), or about 20 m.yr. (on average) older than the granitoids of northwestern Arizona. Barth et al. (2009) document a magmatic gap between 1.73 and 1.69 Ga in the California part of the Mojave province. This magmatic gap coincides approximately with the age of the pre-Yavapai orogeny plutonic rocks in northwestern Arizona. The significance of this observation is discussed below.

Discussion

Any model for the formation and evolution of the Mojave-Yavapai boundary zone must address the following observations and constraints: (1) There is an area of mixed and juvenile-like isotopic signatures in western Arizona (the isotopically mixed Mojave-Yavapai boundary zone). (2) Metavolcanic supracrustal rocks in the boundary zone are dominated by mafic and bimodal compositions; intermediate compositions are rare. (3) Metasedimentary rocks associated with the metavolcanic rocks are overwhelmingly psammitic. These quartz-rich rocks contain appreciable amounts of feldspar, biotite, and lesser amounts of garnet ± hornblende; i.e., they likely represent compositionally immature sandstone and siltstone protoliths and imply some "communication" with a continental source. (4) The plutonic rocks are compositionally variable, and a significant number are of intermediate

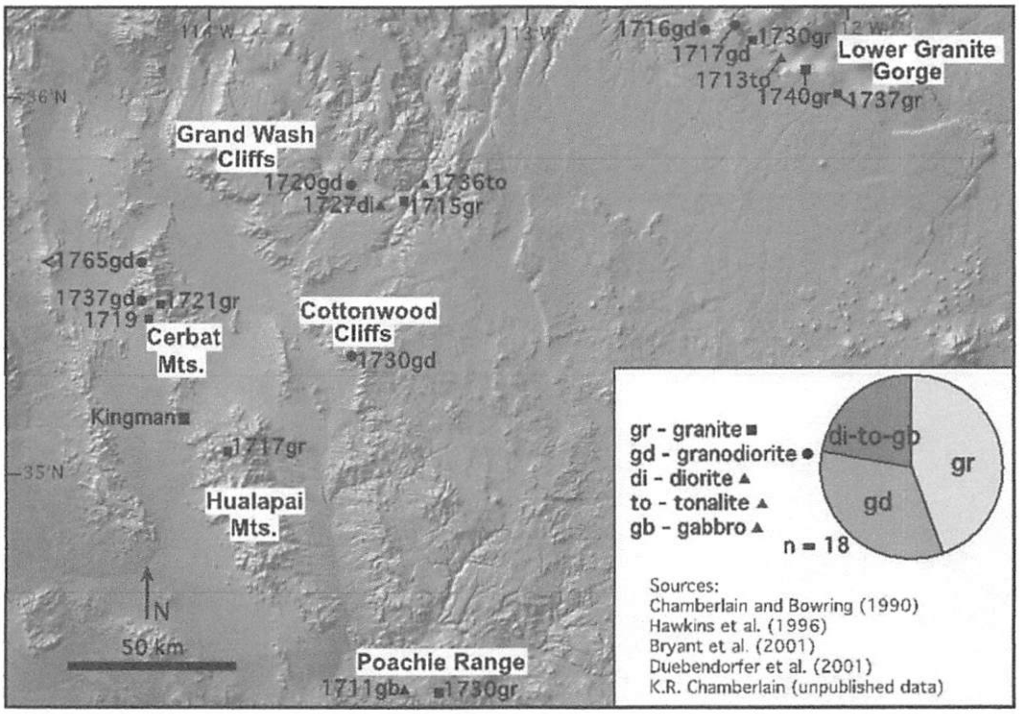

Figure 6. GeoMapApp (http://www.geomapapp.org) image of northwestern Arizona showing composition, distribution, and age of pre-1.71 Ga rocks. The 1.71 Ga cutoff was chosen to include only rocks that clearly predate the ca. 1700 Ma Yavapai-Ivanpah orogeny. Note that the plutonic rocks span the entire range of granitoid compositions and include a significant number of intermediate rocks. For area of figure, compare locations of Kingman and several mountain ranges on figures 1 and 3. A color version of this figure is available online.

compositions. (5) The plutonic rocks are generally 5–15 m.yr. younger than the supracrustal rocks they intrude. (6) Pre-Yavapai orogeny (1.735–1.71 Ga) magmatism in the Arizona Mojave subprovince corresponds temporally with a magmatic gap (1.73–1.69 Ga) in the California (eastern) Mojave subprovince. (7) The nature of the basement on which the supracrustal rocks were deposited in western Arizona is not known; however, compositionally similar supracrustal rocks in the western Mojave province (San Bernardino Mountains) were likely deposited on thin oceanic crust (Barth et al. 2009; Wooden et al. 2012). This is consistent with the volumetrically minor but widely distributed ultramafic rocks present throughout western Arizona as well as the massive sulfide deposits associated with metamorphosed pillow basalts in the Hualapai Mountains.

Supracrustal rocks in four mountain ranges in northwestern Arizona are dominated by bimodal or mafic volcanic rocks and compositionally immature quartzites (psammites), with minor pelites, ultramafic rocks, carbonate, and chert. Bimodal metavolcanic rocks are typical of rift settings (e.g., Menzies et al. 2002) but also occur in oceanic island arcs (e.g., Greater Antilles [Jolly et al. 2008], northern Izu-Bonin arc [Notsu et al. 1987; Tamura and Tatsumi 2002], and parts of the Tonga-Kermadec arc [Smith et al. 2003]). In bimodal oceanic island arc settings, however, sediments associated with the bimodal volcanic rocks are dominated by volcanogenic sedimentary rocks with subordinate amounts of pelagic and hemipelagic sediments, silts, clays, and carbonates (Nishimura et al. 1992; Tucholke 2002; Draut and Clift 2006). The large volume of quartz-rich detritus in the northwestern Arizona supracrustal rocks coupled with the lack of voluminous volcanogenic sediments suggests but does not unequivocally prove derivation from a continental source and leads us to favor a back-arc basin setting for these rocks, as suggested by Strickland et al. (2013).

Tectonic Model for Eastern Mojave Province

The geologic data necessary to construct an actualistic model for the original tectonic setting of the Mojave-Yavapai boundary zone are not available;

therefore, the problem is severely underconstrained. For example, the nature of Mojave province basement—whether continental, oceanic, transitional, or composite—is unknown, as is the polarity of any subduction zones. Nevertheless, the following is a testable model for the pre-Yavapai/Ivanpah orogeny (>1.71 Ga) tectonic evolution of the Mojave-Yavapai boundary zone. This model has conceptual roots in the crustal growth models of Collins (2002), J. V. Jones et al. (2009), D. S. Jones et al. (2010), and Jones and Thrane (2012).

The differences in age and trace-element geochemistry between the western and eastern Mojave province documented by Coleman et al. (2002) and Barth et al. (2009) permit, but do not require, the presence of a structure between them. In this model, the eastern and western parts of the Mojave province are viewed as separate and distinct tectonic blocks of isotopically evolved crust. This is consistent with the proposal of Powell (1993) that a suture between autochthonous and allochthonous Proterozoic terranes exists between the western and eastern Mojave province.

For the time interval 1.76–1.74 Ga, I propose a west-facing arc in the eastern (California) Mojave subprovince, with east-dipping subduction of oceanic lithosphere attached to the western Mojave province at its trailing edge (fig. 7*A*). This oceanic lithosphere may have been produced by earlier intra-arc rifting of a combined western/eastern Mojave arc. Closing of this rift could result in eastwardsubduction that caused the early 1.76–1.74 arc magmatism recorded in the Ivanpah, New York, and Old Woman/Piute Mountains (Flodin et al. 1997; Barth et al. 2009; Wooden et al. 2012). At or before 1.74 Ga, slab rollback resulted in the formation of a back-arc basin in the Arizona part of the eastern Mojave province (the Cerbat, Peacock, and Hualapai Mountains and the Cottonwood Cliffs). This back-arc basin was spatially coincident with the area of juvenile to mixed Pb isotopic compositions that defines the Mojave-Yavapai boundary zone, as proposed by Duebendorfer et al. (2006). Back-arc rifting would have produced the isotopically mixed signature of the boundary zone via the introduction of primitive magmas and the mixing of those magmas with isotopically evolved, incompletely rifted Mojave-type crust (fig. 7*A*). Likewise, the introduction of primitive mafic magmas into more evolved Mojave-type crust could explain the presence of the bimodal supracrustal successions in northwestern Arizona. The large volume of quartz-rich metasedimentary rocks associated with the bimodal metavolcanic sequences may have been derived from the arc rocks of the eastern California (Ivanpah, New York Mountains) arc and possibly, to a lesser extent, from the isotopically evolved rocks of the Bagdad block (Wooden and DeWitt, 1991; fig. 7*A*).

The 1.76–1.74 Ga time interval also coincides with arc magmatism in the juvenile Yavapai province of Arizona, the oldest rocks of which are ~1.75 Ga (Karlstrom and Bowring 1988, 1993). Although there is no direct evidence for the polarity of the subduction zone associated with the Yavapai arc, an east-dipping subduction zone is proposed because of (1) the inferred west-to-southwest tectonic transport direction during D_1 recorded in rocks of both the eastern Mojave and Yavapai provinces (discussed above), and (2) evidence of tectonic burial of the eastern Mojave province to depths >20–25 km (see metamorphic conditions in the "Supracrustal Rocks" section). Both of these observations are consistent with thrusting of the Yavapai arc over the eastern margin of the Mojave province during D_1, as proposed by Duebendorfer et al. (2001). Timing of metamorphism due to tectonic burial is constrained only in the Cerbat Mountains, where Duebendorfer et al. (2001) demonstrated that early metamorphism occurred during D_1 deformation, between 1.74 and 1.72 Ga.

Barth et al. (2009) documented a 1.73–1.69 Ga magmatic gap in both the western and eastern (California) Mojave province. As noted above (fig. 6), pre-Yavapai orogeny granitoids in northwestern Arizona range in age from ca. 1.735–1.715 Ga, coincident with the early part of the magmatic gap in eastern California. The eastward migration of arc magmatism into western Arizona may have been caused by increased coupling between the slab and the eastern California arc due to shallowing of the subducting slab as result of increased convergence rate, introduction of anomalously thick oceanic crust into the subduction zone, or both (fig. 7*B*). Slab shallowing could explain both the magmatic gap in eastern California and the migration of arc-related magmatism into northwestern Arizona spatially coincident with the earlier back-arc basin.

Coincident with eastward migration of the arc into northwestern Arizona, the Yavapai arc impinged on the easternmost Mojave province (Arizona), resulting in D_1 deformation and M_1 metamorphism (Duebendorfer et al. 2001; fig. 7*C*). Continued collision resulted in crustal overthickening, inception of middle to lower crustal melting, and gravitational collapse sometime before the ca. 1.70 Yavapai orogeny, as proposed by Bonamici (2007) and Bonamici and Duebendorfer (2009).

This model is similar to the tectonic switching model of Collins (2002), in which slab rollback induces extension in the overriding plate, either

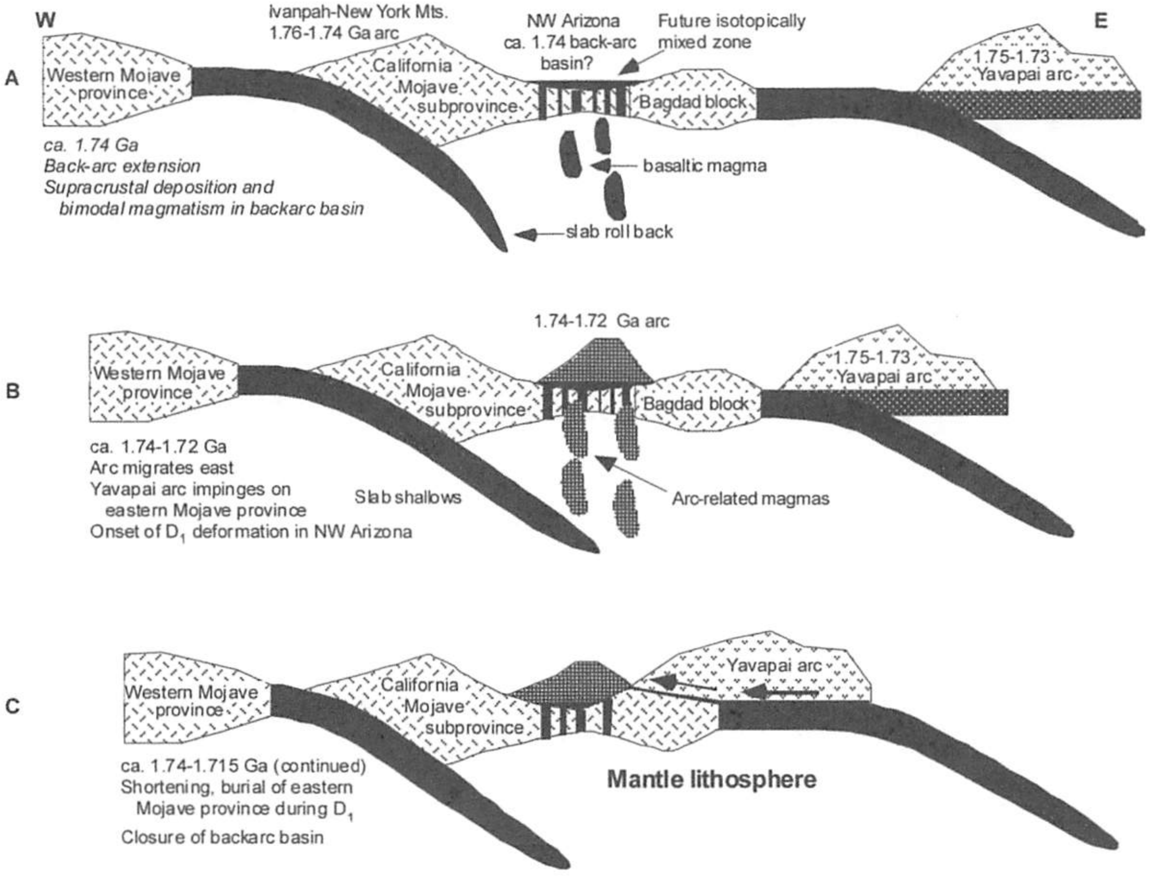

Figure 7. Pre-Yavapai orogeny tectonic model for eastern Mojave province. *A*, Eastward subduction of oceanic lithosphere forms arc in the Ivanpah-New York Mountains area of eastern California between 1.76 and 1.74 Ma. The Yavapai arc is also active at this time (Karlstrom and Bowring 1993). Slab rollback results in the formation of a back-arc basin in the Arizona Mojave subprovince. Partial melting of the asthenosphere initiates basaltic magmatism. Introduction of heat by the basalt causes partial melting of the eastern Mojave crust and consequent rhyolitic magmatism forming bimodal supracrustal rocks. Quartz-rich detritus is derived from the eastern California arc and possibly the Bagdad block. The mixing of juvenile basaltic material and eastern Mojave crust results in the formation of the isotopically mixed Mojave-Yavapai boundary zone. *B*, Arc migrates east into western Arizona (former site of the back-arc basin) due to shallowing of the subducting slab resulting from the increased convergence rate, the introduction of anomalously thick oceanic crust into the subduction zone, or both. The eastern California arc shuts off. *C*, Due to increased coupling along the subduction zone, the Yavapai arc impinges on the easternmost Mojave province resulting in D_1 deformation, M_1 metamorphism, and tectonic burial to 20–25 km. The basin closes by thrust faulting. Speculatively, the Yavapai arc basement (oceanic lithosphere) is detached on impingement of the Yavapai arc with the eastern Mojave province. Continued collision results in crustal overthickening, inception of middle to lower crustal melting, and gravitational collapse sometime before the ca. 1.70 Yavapai orogeny (not shown), as proposed by Bonamici (2007) and Bonamici and Duebendorfer (2009).

splitting the arc or forming a back-arc basin. Subsequent slab shallowing or the intermittent arrival of anomalously thick oceanic crust (e.g., an oceanic plateau) results in contractional closure of the back-arc basin and thickening in the arc–back-arc region. Collins (2002) proposes that an extension/contraction cycle can occur over time intervals of 10–15 m.yr., which is well within the time range that we propose for the Mojave-Yavapai boundary zone. More recently, Armit et al. (2012) documented tectonic burial followed by exhumation to near-surface conditions within a 6 m.yr. period in the northern Mount Painter province, Australia. This model is also very similar to the models of J. V. Jones et al. (2009), D. S. Jones et al. (2010), and Jones and Thrane (2012), which are discussed in the next section.

Comparison with Other Regions

Paleoproterozoic rocks in the Black Canyon–Gunnison-Salida region may also record a similar history to rocks of the Mojave-Yavapai boundary zone, although there is no evidence there for amixed isotopic signature. The oldest rocks in this region are the supracrustal Dubois (1770–1750 Ma) and Cochetopa (1740–1730 Ma) sequences that comprise intercalated tholeiitic metabasalt and high-silica metarhyolite, a bimodal succession (Condie and Nuter 1981; Bickford and Boardman 1984; Boardman 1986; Boardman and Condie 1986; Condie 1986), and volcaniclastic (Bickford and Boardman 1984; Condie and Knoper 1986; Bickford et al. 1989) and quartz-rich (Hansen and Peterman 1968; Hansen 1971; Jessup et al. 2006) metasedimentary rocks. The bimodality of the metavolcanic rocks led Condie and Nuter (1981) to suggest that these rocks were deposited in an arc or immature back-arc extensional basin. Bickford and Hill (2007) pointed out that andesite and basaltic andesite, typical components of modern arcs, are rare in the Black Canyon–Gunnison-Salida region and proposed an extensional tectonic setting for these rocks. Astatke (1989), however, interpreted the Dubois succession as representing a primitive island arc that was rifted at 1740 Ma, forming the basin into which the Cochetopa succession was deposited. Inherited zircons as old as 2520 Ma (Hill and Bickford 2001) and Hf isotopic studies (Bickford et al. 2008) indicate the involvement of older crust during 1.78–1.70 Ga magmatism in the region.

A suite of calc-alkaline tonalite, granodiorite, and granite plutons that are 15–20 m.yr. younger (e.g., Reed et al. 1993, and references therein; Bickford et al. 2008) intrudes the supracrustal rocks. Reed et al. (1993) interpreted these plutonic rocks as having formed in an arc setting. Bickford et al. (1989) noted the presence of younger (1700–1660 Ma) granitic plutons in the Black Canyon–Gunnison-Salida region. This history of bimodal volcanism and attendant siliciclastic deposition in an extensional setting followed by 15–20 m.yr. younger, largely intermediate-composition calc-alkaline magmatism is strikingly similar to the inferred history of the Mojave/Yavapai boundary zone and may imply a common history for the two regions.

Additional studies throughout the Paleoproterozoic orogen of southwestern Laurentia have proposed cycles of extension or rift-related basin formation, followed by basin closure, shortening, and magmatism. For example, Condie (1982) invoked several periods of extensional back-arc basin associated with a southward-migrating continental margin arc system to explain the accretion of 1300 km of continental crust to the Archean Wyoming craton. After their formation, these basins were subsequently closed due to arc collision. In this model, crustal growth is achieved by both bimodal magmatism associated with back-arc basin development and arc magmatism and collision.

J. V. Jones et al. (2009, 2010) proposed a model to explain basin formation, deposition of 1.70–1.68 Ga supermature quartzites, subsequent basin closure, and associated deformation in the Yavapai province of Colorado and northern New Mexico. In their model, back-arc basin formation, quartzite deposition, and associated felsic magmatism occurred in the upper plate of a north-dipping subduction zone that was undergoing "slab rollback following the ca. 1.7 Ga culmination of the Yavapai orogeny" (J. V. Jones et al. 2009, p. 260). The quartzite successions were subsequently deformed and shortened by 35%–50% during the Mazatzal orogeny ca. 1.63 Ga.

D. S. Jones et al. (2010) and Jones and Thane (2012) invoked a similar model to explain basin formation and deformation in the Lester Mountain area, northern Park Range, Colorado, about 25 km south of the Colorado-Wyoming border. Metasedimentary and metavolcanic rocks in the Lester Mountain area are interpreted to have formed in a ca. 1.76 Ga back-arc basin, produced by slab rollback, that separated the 1.78–1.77 Ga Green Mountain arc from the southern margin of the Archean Wyoming craton. Basin closure and related deformation occurred during accretion of the Green Mountain arc to the southern margin of the Wyoming craton ca. 1.75 Ga (Jones and Thane 2012).

Conclusions

Paleoproterozoic supracrustal successions (>1.73 Ga) associated with the Mojave-Yavapai boundary zone in northwestern Arizona consist largely of bimodal metavolcanic and siliciclastic metasedimentary rocks that are intruded by plutons that are 5–15 m.yr. younger and span the entire compositional range of granitoids. Supracrustal rocks are interpreted to have formed in a back-arc rift basin associated with rollback of an east-dipping subducting slab that produced arc magmas at 1.76–1.74 Ga in eastern California. At 1.74–1.72 Ga, increased coupling between the slab and the overriding plate resulted in closure of the back-arc basin and eastward migration of the arc to a position spatially coincident with the former back-arc basin. These events were followed closely by the thrusting of Yavapai province rocks over the basin (D_1), the tectonic burial of supracrustal rock to >20 km, and ultimately the gravitational collapse of the orogen. These events predated the 1.70–1.68 Ga Yavapai orogeny and occurred over a time span of 10–20 m.yr. Similar time intervals for tectonic switching have been documented from the Lachlan orogen of eastern Australia. Crustal growth in the Paleoproterozoic orogen in southwestern Laurentia was accomplished by both rifting-related magmatic additions and by arc accretion, processes that are not mutually exclusive. The cycle of extension and associated basin formation followed by basin closure, deformation, metamorphism, magmatism, and arc accretion appears to have been widely distributed in space and time throughout the Paleoproterozoic orogen of southwestern Laurentia and collectively may be the principal mechanisms by which a ca. 1300 km belt of material was added to the southern margin of the Wyoming craton between 1790 and 1600 Ma.

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