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Assembling and Disassembling California: A Zircon and Monazite Geochronologic Framework for Proterozoic Crustal Evolution in Southern California

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ABSTRACT

The Mojave province in southern California preserves a comparatively complete record of assembly, postorogenic sedimentation, and rifting along the southwestern North American continental margin. The oldest exposed rocks are metasedimentary gneisses and amphibolite, enclosing intrusive suites that range from tonalite and quartz monzodiorite to granite with minor trondhjemite. Discrete magmatic episodes occurred at approximately 1790–1730 and 1690–1640 Ma. Evidence from detrital and premagmatic zircons indicates that recycling of 1900–1790 Ma Paleoproterozoic crust formed the unique isotopic character of the Mojave province. Peak metamorphic conditions in the Mojave province reached middle amphibolite to granulite facies; metamorphism occurred locally from 1795 to 1640 Ma, with widespread evidence for metamorphism at 1711–1689 and 1670–1650 Ma. Structures record early, tight to isoclinal folding and penetrative west-vergent shear during the final metamorphic event in the west Mojave province. Proterozoic basement rocks are overlain by siliciclastic-carbonate sequences of Mesoproterozoic, Neoproterozoic, and Cambrian age, recording environmental change over the course of the transition from stable Mojave crust to the rifted Cordilleran margin. Neoproterozoic quartzites have diverse zircon populations inconsistent with a southwest North American source, which we infer were derived from the western conjugate rift pair within Rodinia, before establishment of the miogeocline. Neoproterozoic-Cambrian miogeoclinal clastic rocks record an end to rifting and establishment of the Cordilleran miogeocline in southern California by latest Neoproterozoic to Early Cambrian time.

Online enhancements: appendixes.

Introduction

Proterozoic plate reconstructions revolve around assembly of the late Proterozoic supercontinent Rodinia, hypothesized to be an amalgam of all significant cratons assembled during the ~1050 Ma Grenville-Kibaran-Sveconorwegian orogenies (Bond et al. 1985; Hoffman 1988; Karlstrom et al. 1999). Central to this supercontinent reconstruction is identification of the Proterozoic conjugate margin of western North America. There are two significant obstacles preventing accurate positioning of the western Laurentian margin with respect to the other cratons in the Proterozoic. First, the well-defined transcontinental Proterozoic orogenic belts of southern Laurentia are truncated on the southwest by the Mojave crustal province. Second, some 600 m.yr. of Cordilleran extension, compression, and transform deformation and associated magmatism strongly modified the rifted western Laurentian margin. Consequently, unraveling the Proterozoic magmatic and deformational history of the Mojave crustal province through the screen of younger tectonism and magmatism is key to po-

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sitioning Laurentia with respect to the cratons that would later comprise eastern Gondwana. The formation age and deformation history of Proterozoic rocks in the Mojave crustal province thus provide an important link to understanding the construction and destruction of the Proterozoic supercontinent.

Paleoproterozoic crystalline basement rocks and sedimentary overlap sequences exposed in southwestern California are the western exposed part of the Mojave crustal province of the southwestern United States. These basement rocks and overlap sequences hold a 1.3-billion-year record of crust formation and crustal evolution along what would finally become the southwestern margin of the North American craton by Cambrian time. Paleoproterozoic metasedimentary and metaigneous rocks record the growth and stabilization of continental crust in this region between about 1.8 and 1.63 Ga. Continental basement is locally overlain by the remnants of three siliciclastic-carbonate sedimentary sequences of Mesoproterozoic, Neoproterozoic, and Cambrian age. These sedimentary sequences, probably deposited during three discrete episodes ca. 1.63–1.49, 0.62–0.57, and 0.57–0.50 Ga, record environmental change over the course of the transition from stable continental crust to the rifted Cordilleran margin of southwestern North America. Both crystalline rocks and cover sequences contain within them detrital zircons, whose provenance can extend the record of crust formation and evolution in the Mojave region backward in time a further 1.6 billion years to at least 3.45 Ga. Precise ages of these older detrital zircons provide a picture of the sources of sediment that contributed to initial crust formation and to sedimentary sequences that record rifting and final fragmentation of supercontinent crust.

In this study, we report an ion microprobe geochronologic and geochemical investigation of the largest areas of Precambrian rock exposure within the west Mojave crustal province. We link geochronologic and geochemical data relevant to the west Mojave province to the larger Mojave province through comparison to selected samples from the Ivanpah Valley region of the east Mojave province (fig. 1). The west Mojave province focus area was selected for three reasons: because the comparatively low grade of metamorphism in comparison to the east Mojave province has allowed preservation of a more complete record of Paleoproterozoic crust formation and early evolution, because of its position at the craton edge, and because of the variety of preserved supracrustal cover sequences that onlap the Paleoproterozoic craton. Because the study area lies within the Phanerozoic Cordilleran orogenic belt, we focus on zircon and monazite U-Pb systematics to characterize the Proterozoic history of this region through the overprint of Cordilleran thermal and deformational events.

Geologic Setting of Paleoproterozoic Basement Rocks

Exposed Proterozoic basement rocks in southwestern North America primarily comprise the Yavapai and Mazatzal provinces, but the Mojave crustal province intervenes between the craton interior and the plate margin. Bulk rock isotopic and conventional bulk fraction U-Pb zircon studies suggest that the distinctive character of the east Mojave crustal province derives from the incorporation into ca. 1.7 Ga orthogneisses and paragneisses of older Paleoproterozoic and Archean detrital and inherited material (Bennett and DePaolo 1987; Wooden et al. 1988; Wooden and Miller 1990; Rämö and Calzia 1998; Barth et al. 2000); rarely, older Paleoproterozoic rocks have also been identified (Wooden et al. 1994; Hawkins et al. 1996), but the origin of these rocks is unclear as a result of the isolated nature of the exposures and the uncertain effect of later metamorphism on their contained zircons.

The west Mojave province is exposed along the Paleozoic hinge line in the central and eastern Transverse Ranges (fig. 1). Here the Proterozoic basement is somewhat lower grade than granulite grade east Mojave province, making the rocks more amenable to elucidation of processes and timing of crustal assembly. Furthermore, this region is the location of a proposed suture between autochthonous and allochthonous Proterozoic basement terranes (Powell 1981, 1993), so clarification of the geologic evolution of Proterozoic basement should provide insight into both the assembly and the later evolution of Mojave province crust. In order to better constrain the timing of crustal assembly, we analyzed monazite and zircons from basement rock samples in the San Bernardino Mountains and in the eastern Transverse Ranges.

Proterozoic basement of the west Mojave province in the San Bernardino Mountains includes orthogneisses ranging in age from ca. 1.78 to 1.68 Ga, overprinted by a high-grade metamorphic event at ca. 1.74 Ga (Barth et al. 2000). However, the timing of the latest regional metamorphism is unknown, as is the timing of development of the penetrative west-dipping D_2 fabric observed in rocks as young as 1.68 Ga. Additional age data presented here expand the approach of that earlier study, utilizing higher-resolution SEM-CL to characterize

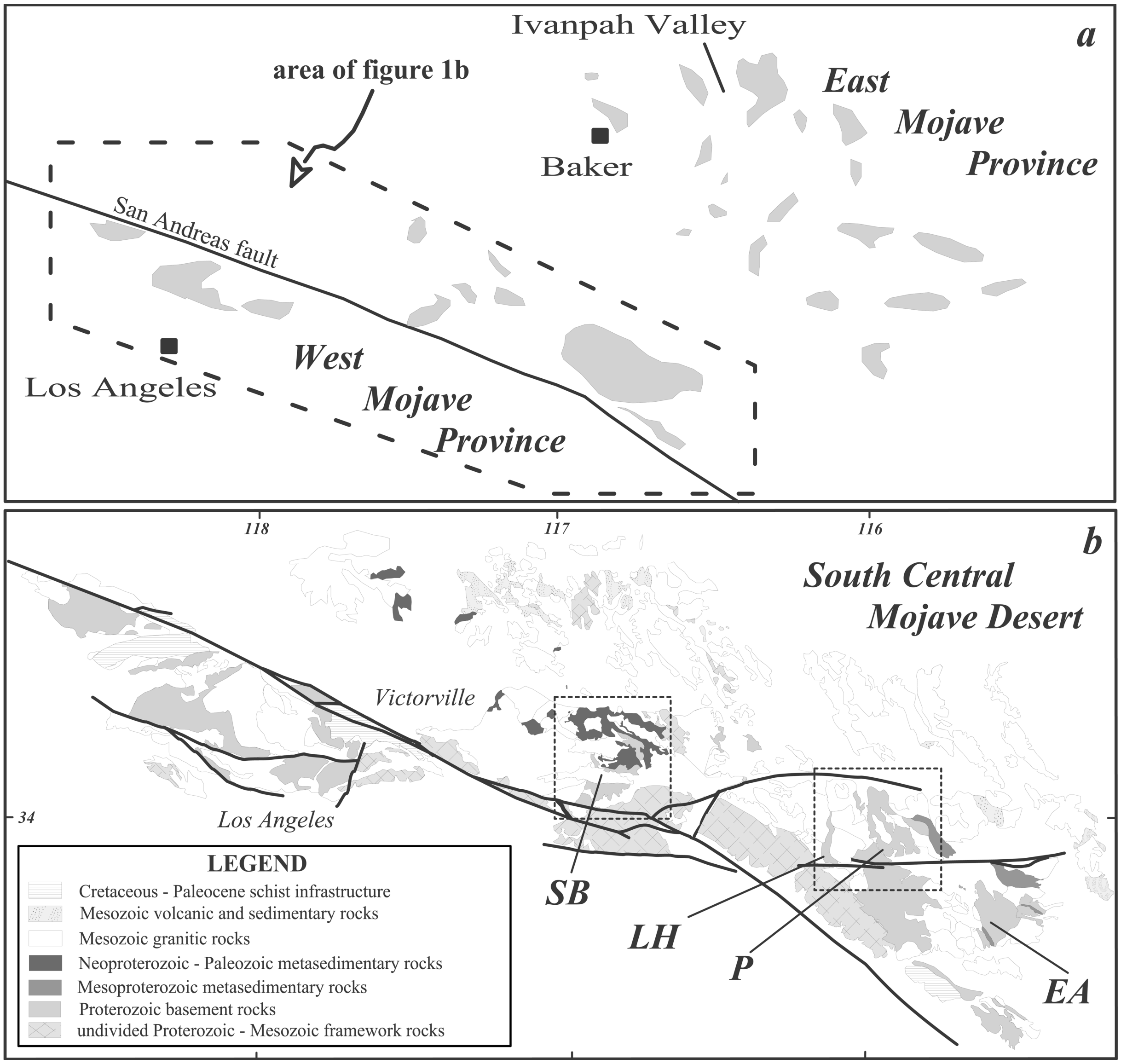

Figure 1. *a*, Location map of Proterozoic basement rocks of the Mojave crustal province in California. *b*, Geologic map of the central and eastern Transverse Ranges. Boxes show the locations of study areas with significant exposure of west Mojave province basement rocks and siliciclastic-carbonate cover sequences. *SB* = San Bernardino Mountains, *LH* = Lost Horse Mountains, *P* = Pinto Mountains, *EA* = Eagle Mountains.

compositional domains and guide domainal ion microprobe analysis (apps. A, B, available in the online edition and from the *Journal of Geology* office). These new data illuminate the early detrital input of preexisting crustal material, expand the regional intrusive history, and provide better limits on the timing of high-grade metamorphism and fabric development in the Mojave province.

Older Gneisses. The oldest recognized rocks in the west Mojave province are micaceous gneisses and amphibolites. Biotite + muscovite gneisses are isoclinally folded and metamorphosed to amphibolite facies, with local evidence of migmatization, and are commonly associated with hornblende + plagioclase amphibolites. Amphibolites have a relatively restricted range in composition, with SiO_2 typically between 46% and 49% and minor and trace element abundances similar to low-K tholeiitic igneous rocks. Trace element compositions are consistent with a protolith similar to modern volcanic and plutonic rocks found in oceanic ridge settings (fig. 2). Coleman et al. (1999) estimated an age of ca. 1.81 Ga for these amphibolites on the basis of whole rock Nd isotopic ratios, and initial ^{143}Nd/^{144}Nd suggest an enriched mantle source.

U-Pb systematics in zircons provide insight into the origin of the protolith of the associated micaceous gneisses. These gneisses contain zircons with a variety of shapes and zoning patterns, but most grains contain a more homogeneous rim or rims that truncate internal zonation. Because these rims overgrow a variety of core compositions and typically yield younger ages and lower Th/U, we infer that they record the timing of a later metamorphic event associated with zircon dissolution and regrowth, commonly in the presence of an oxidizing fluid and a Th-enriched phase. In contrast, zircon cores yield the ages of detritus incorporated in the sedimentary protoliths of the micaceous gneisses. A compilation of the ^{207}Pb*/^{206}Pb* ages of only the most concordant of these detrital zircon cores (fig. 3) indicates that early crust formation in the Mojave province occurred by deposition of immature sediment, derived from nearby 1.98–1.8 Ga crust, onto a thin, enriched oceanic basement.

Magmatism and Metamorphism. This early, oceanic basement and its sedimentary cover was intruded by a variety of plutonic rocks, now exposed as augen and granitic orthogneisses interleaved with amphibolite and micaceous gneisses. Orthogneisses typically contain readily identifiable euhedral to subhedral zircon cores that yield well-defined discordia arrays indicative of Pb loss from primary magmatic zircon (fig. 4). Many orthogneisses also contain a volumetrically minor (<10%) yet isotopically distinct population of significantly older grain cores, which we infer are premagmatic and indicative of the involvement of Archean and older Paleoproterozoic crust in generation of the protolith igneous rock. Older orthogneisses also contain zircon rims, embayment fillings, and isolated CL-dark grains, usually Th depleted and five to 10 times richer in U; these zircon domains yield discordia arrays indicative of Pb loss in zircon with a significantly younger crystallization age than the magmatic cores (fig. 4). On the basis of their compositions and textures and paralleling the inferred history of the paragneisses, we infer that these U-enriched zircons record the timing of high-grade metamorphism associated with zircon dissolution and regrowth. Some samples contain a minor population of zircons with comparably high U but much younger ages, suggesting minor thermal events in the Mesoproterozoic and Mesozoic associated with loss of radiogenic Pb and/or minor new zircon growth.

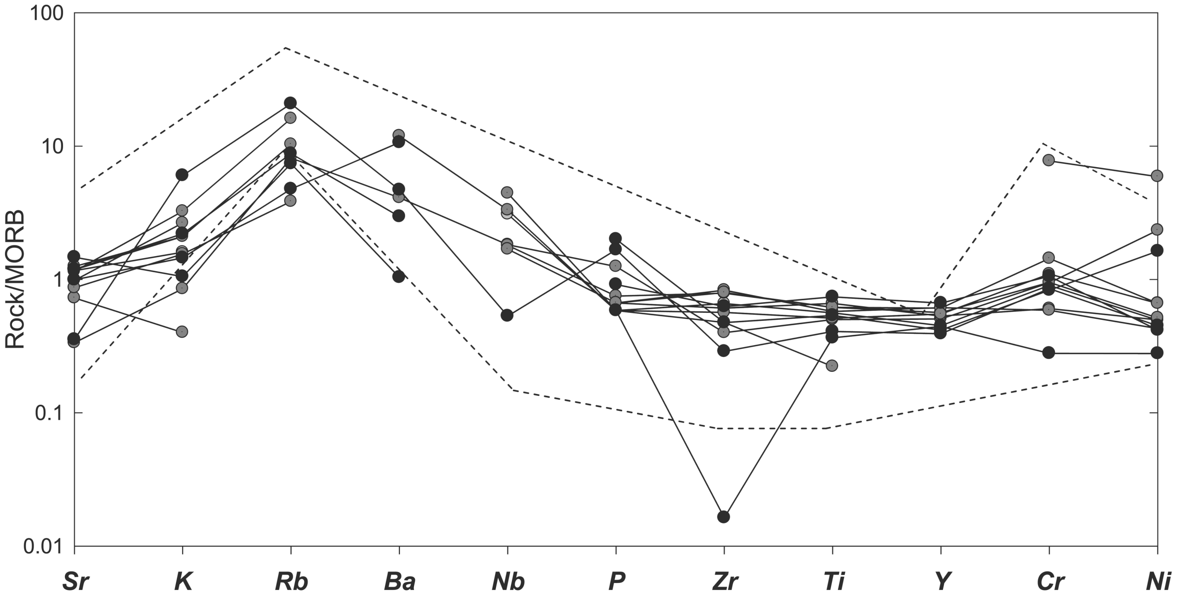

Figure 2. Geochemistry of older amphibolites from the west Mojave province, normalized to modern mid-ocean ridge basalt (MORB; Hart et al. 1999). The dashed lines illustrate the compositional range of east Mojave amphibolites (Miller and Wooden 1992). Note the slight enrichment in Rb and Ba and slight depletion in high field strength elements (HFSEs) in west Mojave amphibolites compared with MORB. East Mojave samples are similar but exhibit greater average large ion lithophile element enrichment and HFSE depletion.

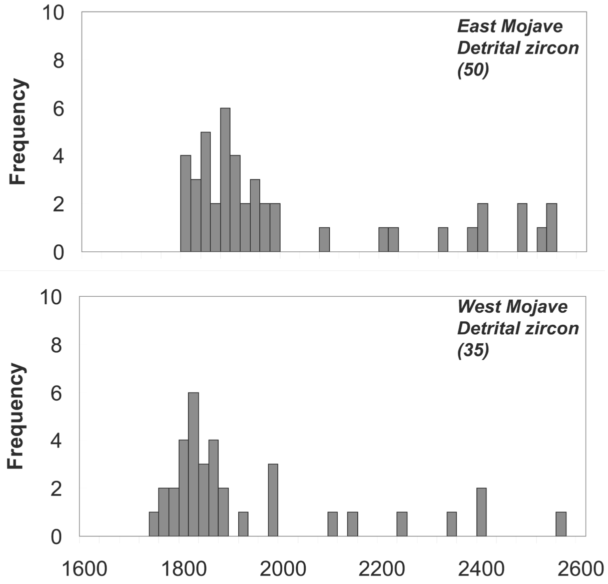

Figure 3. Histograms of detrital zircon ages in older micaceous gneiss of the Mojave province. Note that 1.8–2.0 Ga detrital zircons predominate in both the west and the east Mojave province, with lesser older Paleoproterozoic and Archean grains.

Utilizing this analytical approach, 16 orthogneisses from the west Mojave province and nine from the east Mojave province yield magmatic ages ranging from 1783 ± 12 to 1650 ± 18 Ma (table 1). A compilation of crystallization ages (fig. 5) indicates two discrete episodes of magmatism in the Mojave province: an early phase initiated at about 1.79 Ga and extending to as late as 1.73 Ga, and a late phase initiated at about 1.69 Ga and extending to as late as 1.64 Ga.

These two intrusive phases appear to have been compositionally distinct and therefore probably bracket an important change in tectonic setting and/or crustal thickness in the Mojave province. Bender et al. (1993) reported compositional data for augen orthogneisses from several ranges in the west Mojave province. Our U-Pb results indicate that all the plutons analyzed by Bender et al. (1993) belong to the late intrusive phase (their Joshua Tree, Monument Mountain, Hexie, Soledad, and Frazier Mountain gneisses). Although both early and late phase orthogneisses span a similarly wide range of silica contents (fig. 6), early phase plutons range from low to high K and have lower abundances of iron and high field strength elements (HFSEs) than do late phase plutons. Orthogneisses in the east Mojave province show similar compositional relations. These data indicate that the period between 1.73 and 1.69 Ga corresponds to an important transition to high K and HFSE-enriched magmatism in the Mojave province.

Comparison of the ages of magmatic zircons in orthogneisses and metamorphic zircons from both ortho- and paragneisses provides further insight into the interplay between magmatism and metamorphism in the west Mojave province (fig. 7). Ten paragneisses and older orthogneisses with U-enriched zircon overgrowths yield metamorphic ages of 1711–1682 Ma in the west Mojave province, and paragneiss from the west Mojave and Ivanpah Valley region extend this age range to 1795–1640 Ma (table 1). These data suggest that metamorphism associated with new zircon growth was occurring locally within the Mojave province at least from 1.8 to 1.68 Ga and probably throughout the episodes of voluminous magmatism represented by formation of the orthogneisses. Nevertheless, clustering in these age data suggests that an important metamorphic event in the west Mojave province occurred between 1711 and 1689 Ma, contemporaneous with the Ivanpah Orogeny defined by Wooden and Miller (1990). Thus, we conclude that the Ivanpah Orogeny was a province-wide metamorphic and deformational event, higher grade to the east, and that this orogenic event was associated with a lull in plutonism and a transition in magmatic character to postorogenic, uniformly K and HFSE-enriched late phase magmatism.

Because west Mojave orthogneisses younger than 1.7 Ga commonly contain well-developed D_2 fabrics (Barth et al. 2000), we analyzed monazite from 10 samples of orthogneisses and biotite ± muscovite quartzofeldspathic paragneisses in the San Bernardino Mountains and eastern Transverse Ranges, mostly from samples with well-defined U-Pb zircon ages. Three samples from the San Bernardino Mountains yield moderately normally discordant Proterozoic monazite dates of 1674 ± 16, 1663 ± 10, and 1656 ± 8 Ma (table 1). Two samples contain an additional younger generation of monazite of Cretaceous age. Five samples from the Lost Horse and Pinto mountains yield slightly normally to slightly reversely discordant monazite. Concordia arrays in three samples yield relatively precise upper intercept ages of 1675 ± 6, 1674 ± 23, and 1666 ± 4 Ma. Two samples yield concordia intercepts of 1658 and 1655 Ma with scatter in excess of analytical errors. One sample contains an additional younger generation of monazite of Jurassic age.

From these data, we conclude that amphibolite-grade metamorphism associated with monazite growth in the basement gneisses in the west Mo-

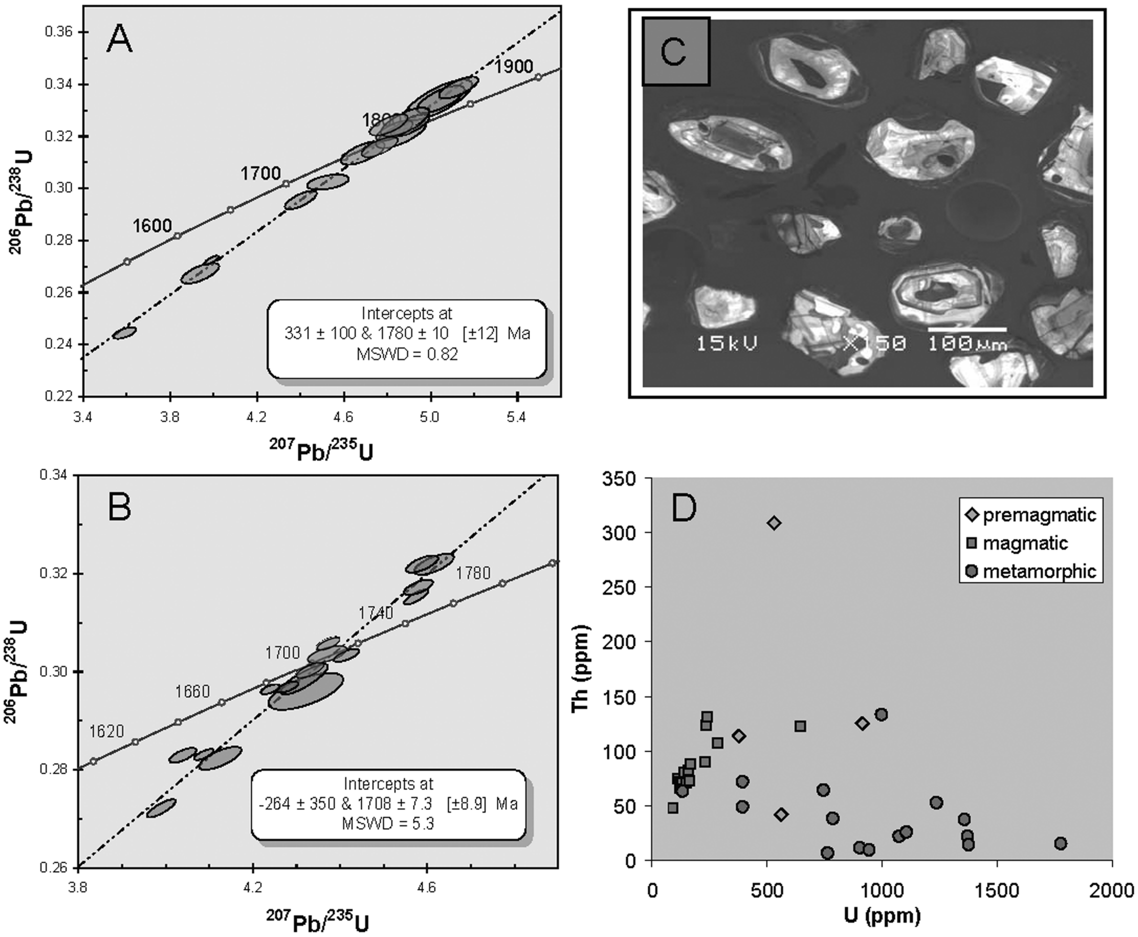

Figure 4. Example of zircon textural relations and geochemistry in an orthogneiss: sample JW326, the trondhjemitic gneiss of Dry Lake. *A*, Concordia diagram for low U, magmatic zircon. Four trondhjemite premagmatic core analyses with ages ranging from 1857 to 2572 Ma are not plotted. *B*, Concordia diagram for U-rich, low Th/U metamorphic zircon. *C*, SEM-CL image of zircons, showing oscillatory zoned cores, fractured and embayed, and CL-dark fracture fillings and overgrowths. *D*, U and Th concentrations in individual zircon textural and chronologic groups.

jave province and penetrative west-vergent fabric development in the San Bernardino Mountains occurred at ca. 1680–1660 Ma (fig. 7). Excess scatter in near-concordant grains indicates that metamorphic growth of monazite may have extended locally to as late as ca. 1630 Ma.

Geology of Quartzite-Carbonate Overlap Sequences

Remnants of three distinct quartzite-rich overlap sequences are preserved in depositional contact with Paleoproterozoic gneisses in the west Mojave province (figs. 1, 8). We analyzed paleocurrent data and U-Pb systematics of detrital zircons in quartzites from each of these sequences to clarify the depositional and rifting history of the southwestern margin of North America, which culminated in rifting and formation of the Paleozoic Cordilleran passive margin.

Pinto Mountain Group. A >1-km-thick sequence of medium-grade and weakly deformed Mesoproterozoic metasedimentary rocks overlies Early Proterozoic basement in the Pinto and Eagle mountains (fig. 8) and includes basal conglomerate and interbedded quartzite, a middle section of cross-bedded quartzite, pelitic rocks, laminated Fe-rich rocks, and an upper section of dolomitic carbonate rocks. Sedimentary structures preserved in quartzites record sediment transport toward the southeast and east.

The nomenclature for this sequence has evolved

Table 1. Geochronologic Summary for Proterozoic Gneisses of the Mojave Province

Sample	Range	Magmatic zircon (Ma)	Metamorphic zircon (Ma)	Monazite (Ma)
JW233 Baldwin Lake	San Bernardino			~81
JW235 Baldwin Lake	San Bernardino	1741 ± 20[a]		~82
JW236 Lightning Gulch	San Bernardino	1773 ± 14[a]		1674 ± 16
JW314 Baldwin Lake	San Bernardino	1656 ± 16		
JW316 Baldwin Lake	San Bernardino	1766 ± 12[a]		1656 ± 8
JW324 Broom Flat	San Bernardino	1681 ± 18		
JW322 Broom Flat	San Bernardino		1682 ± 23	
JW325 Grinnell Mountain	San Bernardino		1684 ± 6	1663 ± 10
JW326 Dry Lake	San Bernardino	1780 ± 10	1706 ± 7	
98280 Bighorn	San Bernardino	1752 ± 9	1704 ± 7	
99299 Erwin Lake	San Bernardino	1650 ± 18		
JW152 White Tank	Pinto	1741 ± 7	1698 ± 10	1666 ± 4
JW153 White Tank	Pinto	1750 ± 18	1705 ± 11	1675 ± 6
JW177 Music Valley	Pinto			1674 ± 23
JW334 Joshua Tree	Pinto			1685 ± 13
02337	Lost Horse		1703 ± 7	
02375	Lost Horse			~1658
02403	Lost Horse			~1655
JT002	Lost Horse		1711 ± 8	
JT003	Lost Horse	1747 ± 14	1689 ± 13	
05588 Monument	Hexie	1666 ± 14		
JW20 granitic gneiss	Ivanpah	1736 ± 6	1691 ± 6	
JW21 augen gneiss	Ivanpah	1766 ± 12	1640 ± 15	
JW23 granite	New York	1658 ± 7		
JW77 granodiorite gneiss	New York	1732 ± 19		
JW79 garnet gneiss	New York		1795 ± 11	
JW97 augen gneiss	Old Woman–Piute	1675 ± 5		
JW101 augen gneiss	Old Woman–Piute	1733 ± 11	1677 ± 11	
JW102 diorite	Old Woman–Piute	1657 ± 7		
JW172 trondhjemitic gneiss	Ivanpah	1759 ± 12		
JW175 gneiss	Marl	1759 ± 9	1672 ± 10	
W660 quartzite	Old Woman–Piute		1674 ± 6	

[a] Age from Barth et al. (2000).

as workers inferred its age and tested potential regional correlations. Cameron (1981) suggested that the cover sequence correlates with lithologically similar metasedimentary rocks of the Big Bear Group exposed in the San Bernardino Mountains to the northwest. Powell (1981) named these rocks the Joshua Tree terrane and suggested correlation with amphibolite-grade metasedimentary rocks to the west. Powell (1993) later renamed these rocks the Placer Canyon assemblage. We call these rocks informally the Pinto Mountain Group after that part of the outcrop belt that is best exposed and least deformed and to avoid implied correlations attached to earlier nomenclature. Our mapping and detrital zircon geochronology indicate that the Pinto Mountain Group is younger than suggested by Powell (1981) yet is too old to be correlated with the Big Bear Group, as suggested by Cameron (1981). Rather, we propose that these rocks represent a postorogenic, pre-1.49 Ga overlap sequence.

Detrital zircons from four quartzite and phyllitic quartzite samples range from angular to subrounded, preserve one to three generations of fine-scale oscillatory zoning, and show no evidence of the extensive fracturing and high U fracture fillings or overgrowths observed in zircons from the underlying basement. About half of the grains preserve discontinuous, CL-bright patches up to about 5 μm thick along their margins that may record minor, low-U metamorphic zircon growth; we avoided this component in selecting analysis spots. All four samples contain a single main population of Paleoproterozoic grains (fig. 9) that range from concordant up to about 80% normally discordant, defining discordia arrays from 1650 to 1800 Ma toward lower intercepts around 200 Ma, consistent with a Mesozoic thermal disturbance similar to that observed in basement rocks. The $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ ages of the most concordant grains (80 of 149 grains ≤10% discordant) provide the best estimate of the age of this principal detrital population, which ranges from 1788 to 1630 Ma. Three of the four samples also contain a second, minor population of Archean grains; the most concordant

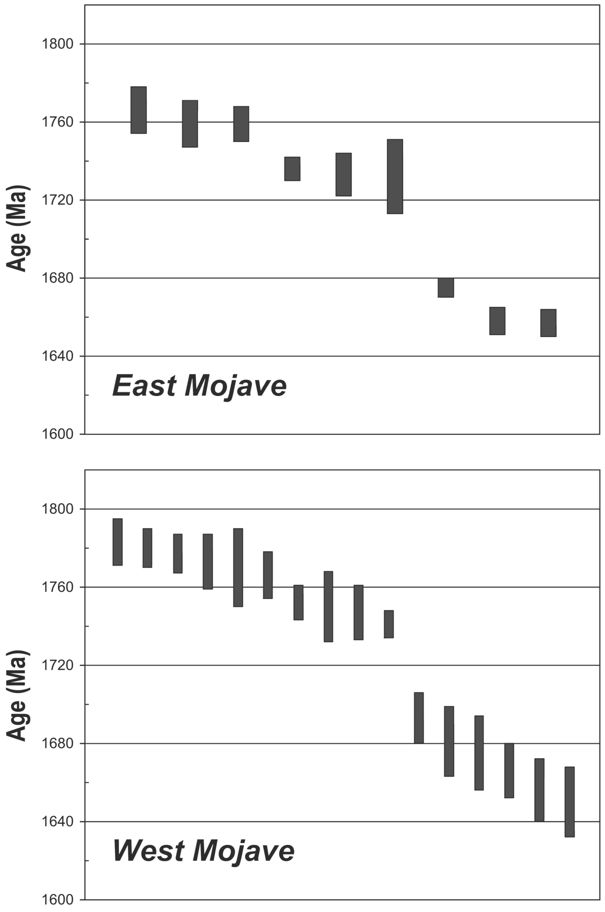

Figure 5. Summary diagram of U-Pb zircon crystallization ages of orthogneisses from the east and west Mojave province (additional data from Barth et al. 2000). Note the two distinct age groupings present in both the west and the east Mojave province. These age groupings define early and late phase plutonism, separated by a magmatic gap between 1.73 and 1.69 Ga.

grains suggest provenance ages of 3.42 and 2.64–2.48 Ga. No reliable grain ages younger than 1630 Ma were obtained in any of these samples, which we therefore take to be the maximum depositional age of the siliciclastic section of the Pinto Mountain Group.

In order to test the potential correlation of the Pinto Mountain Group with deformed metasedimentary sequences exposed further west in the Pinto Mountains, we examined zircons from a quartzite within a package of Joshua Tree terrane metasedimentary rocks and orthogneisses. The Dog Wash quartzite yielded subhedral to rounded zircons; SEM-CL imaging suggests that much of the rounding is due to the presence of CL-dark, subhedral zircon rims that overgrow much more irregularly shaped zircon cores (fig. 9). The cores are of two distinct textural varieties; comparatively CL-bright, subhedral zircon cores display fine-scale oscillatory zoning, contrasting with anhedral zircon cores that display mottled textures in CL images composed of discrete, irregularly shaped dark and bright patches typically about 2–10 μm across. The oscillatory-zoned cores are clearly older than the dark rims, but the relative age of the mottled cores is less certain.

Nineteen oscillatory-zoned cores yielded the oldest observed ages in this sample, with $^{207}\mathrm{Pb}^*/^{206}\mathrm{Pb}^*$ ages ranging from 1783 to 1719 Ma and the lowest U contents and highest Th/U (fig. 9). About 60% of these grains are concordant, yielding ages between 1783 and 1730 Ma. We interpret these as the range in age of the predominant detrital zircon component in this sample. The dark zircon rims are significantly enriched in U and exhibit lower Th/U, with $^{207}\mathrm{Pb}^*/^{206}\mathrm{Pb}^*$ ages between 1704

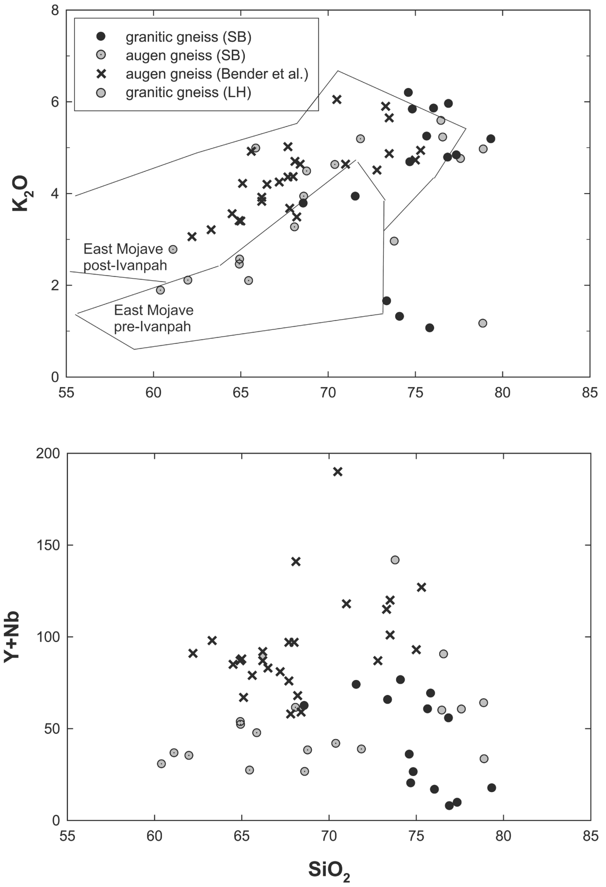

Figure 6. Alkali and high field strength element geochemistry of orthogneisses from the Mojave province. Circles are early phase orthogneisses of the west Mojave province from this study (abbreviations as in fig. 1*b*), and crosses are late phase augen gneisses from Bender et al. (1993). Fields in the top panel represent the compositional range of orthogneisses from the east Mojave province (Miller and Wooden 1992; Flodin et al. 1997). Lines in the top panel separate fields of low, medium, and high K igneous rocks. Note the wide silica range and diverse K contents of early phase gneisses and the K- and HFSE-enriched character of late phase gneisses.

and 1661 Ma. The mottled cores exhibit a range of compositions, from a few with low U and Th/U, similar to the oscillatory-zoned cores, to the majority with much higher U contents and Th/U, similar to that of the dark rims. We interpret these variations to indicate that the grains are composed of domains of mixed age and origin at a scale smaller than the ion beam, and the measured ages are dominated by the age of the dark, U-rich and relatively young component. Observed $^{207}Pb^*/^{206}Pb^*$ ages of these mottled cores range from 1682 to 1582 Ma; however, concordant grains range only from 1682 to 1636 Ma. We interpret this age range as an approximation to the age of the dark component of the mottled cores, and the overlap with the observed age range of the dark rims suggests that the mottled cores record partial recrystallization of older zircon associated with metamorphism of this rock, ultimately overgrown by the dark rims. In summary, we interpret this quartzite to have a provenance in local Paleoproterozoic granitic rocks ranging in age from 1783 to 1730 Ma and to have later enjoyed deformation and metamorphism associated with partial zircon dissolution and low Th/U zircon growth between 1704 and 1636 Ma. We thus infer that the Joshua Tree terrane gneissic metasedimentary and metaigneous rocks are older than (and therefore simply are part of) the Paleoproterozoic crystalline basement on which the Pinto Mountain Group was deposited.

Big Bear Group. A sequence of lower-grade, weakly deformed metasedimentary rocks overlie Paleoproterozoic basement in the San Bernardino

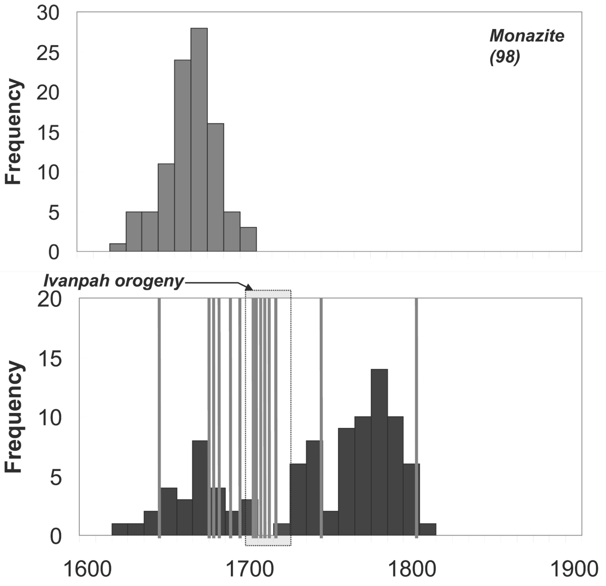

Figure 7. Summary diagram comparing orthogneiss and metamorphic geochronology of the Mojave province. Top panel is a histogram of $^{207}Pb^*/^{206}Pb^*$ ages of the least discordant metamorphic monazites from west Mojave province. Bars in bottom panel illustrate timing of metamorphism recorded by metamorphic zircon rims; for visual reference, these ages are compared with the range of ages of least discordant magmatic zircons in west Mojave orthogneisses. Note that metamorphism is broadly synchronous in time with emplacement of the protoliths of the orthogneisses, yet the Ivanpah Orogeny is marked by the abundance of zircon metamorphic ages and the time gap between early and late phase plutons.

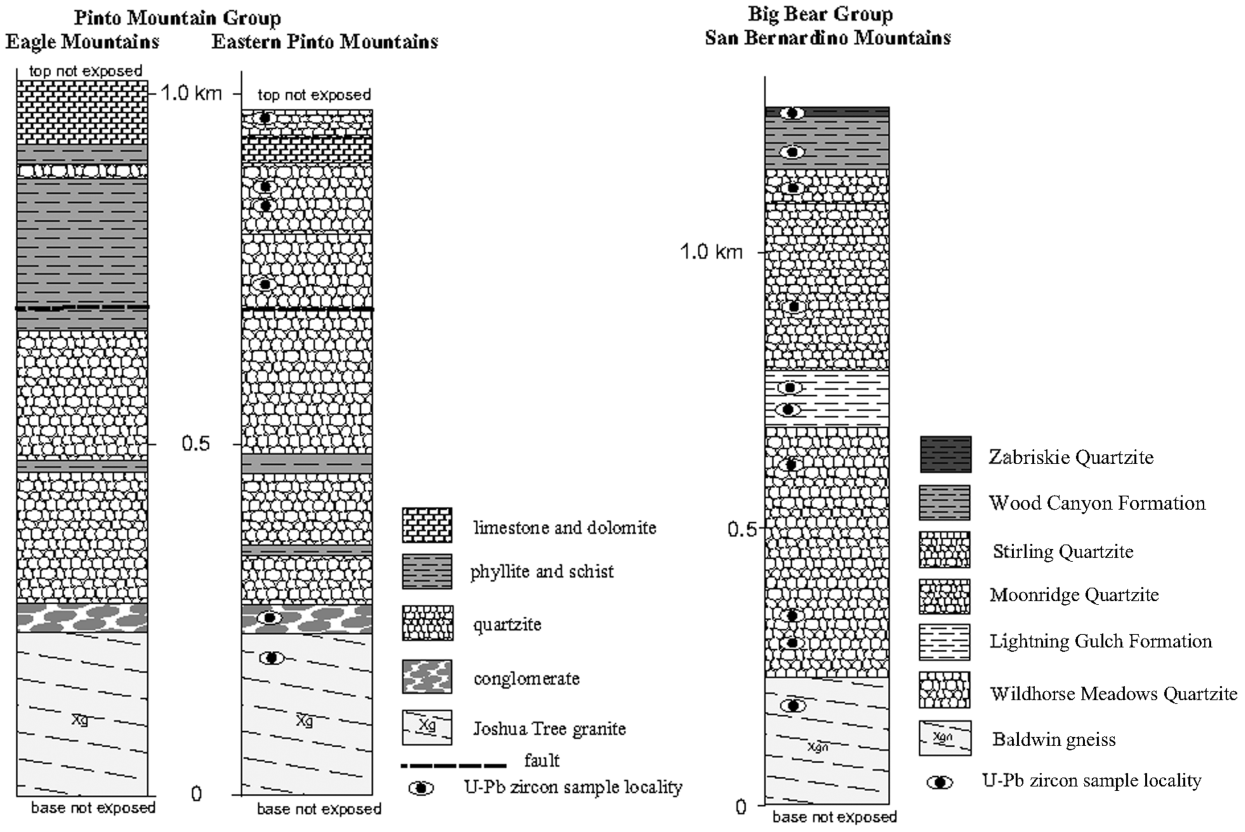

Figure 8. Stratigraphic columns for Proterozoic sedimentary sequences in the Transverse Ranges, showing relative stratigraphic position of detrital zircon sample horizons. The Pinto Mountain Group is a siliciclastic-carbonate sequence that rests unconformably in the Paleoproterozoic basement in the Pinto Mountains and extends southeastward into the Eagle Mountains (Eagle Mountains stratigraphic column adapted from mapping of Powell 1981). The Big Bear Group is a siliciclastic sequence that rests unconformably on the Paleoproterozoic basement in the San Bernardino Mountains (column adapted in part from mapping of Cameron 1981).

Mountains. The nomenclature for these metasedimentary rocks evolved as workers recognized their stratigraphic and structural complexity (see review by Dibblee 1982). We have largely followed the stratigraphic terminology of Stewart and Poole (1975; Stewart 1972; Cameron 1981; Brown 1991; figs. 8, 10), though structural and stratigraphic problems remain. The lowest part of this metasedimentary sequence includes quartzite and phyllite of the Big Bear Group. The lowermost quartzite unit in the Big Bear Group demonstrably overlies Paleoproterozoic gneiss with angular unconformity. In the north central part of the range, the Big Bear Group lies structurally above a sequence of units correlative with the Cordilleran miogeocline, including the Neoproterozoic-Cambrian boundary interval in the upper Stirling Quartzite and overlying Wood Canyon Formation (Signor and Mount 1989; Corsetti and Hagadorn 2000) and overlying Cambrian Zabriskie Quartzite, Carrara Formation, and Bonanza King Formation. Marbles correlative with the Cambrian Nopah, Devonian Sultan, Carboniferous Monte Cristo, and Permian Bird Spring formations have also been identified in fault blocks along the north-central range front (Brown 1991).

Metasedimentary rocks of the Big Bear Group are primarily exposed surrounding Baldwin Lake (fig. 10). In the western two-thirds of the map area, Big Bear Group quartzite and phyllite are generally upright, north to west striking, and lie above Paleoproterozoic gneiss. Although the contact between these two rock units is commonly sheared, at several localities upright basal conglomerate, pebbly quartzite, or quartzite rest with angular unconformity on the underlying gneiss. Both the gneiss and the overlying Big Bear Group are cut by gently to moderately west-dipping normal faults. In the eastern third of the map area, north of Onyx Peak, over-

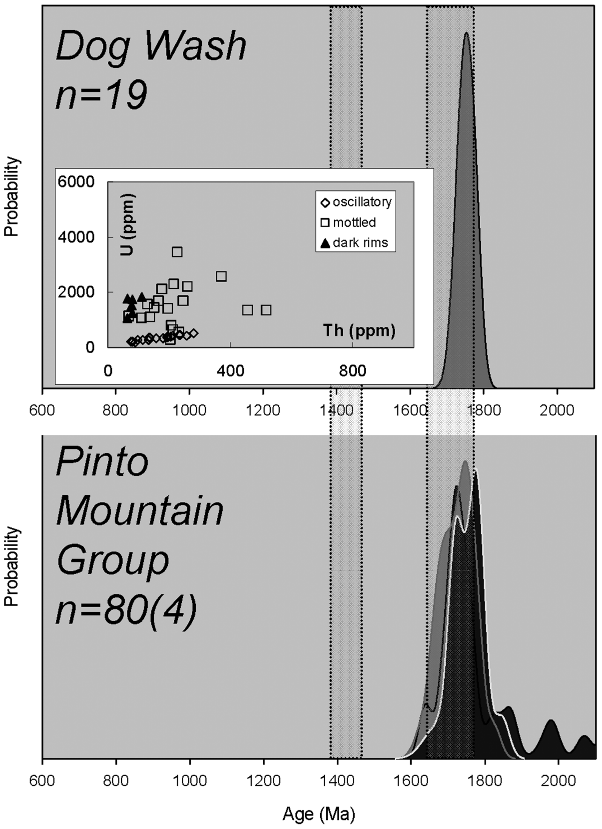

Figure 9. Cumulative probability plot of ages of detrital zircons from the Pinto Mountain Group (80 most concordant zircons in four samples; for sample horizons, see fig. 8). All four Pinto Mountain Group quartzites show similar detrital zircon age distributions, defining a maximum depositional age of ca. 1630 Ma. Lightly shaded bars show the range of ages of basement igneous rocks; lack of ca. 1400–1450 Ma detrital zircons suggests that the Pinto Mountain Group was deposited before 1450 Ma. Top panel compares age data for quartzite of Dog Wash in the Joshua Tree terrane (19 most concordant zircons). Inset shows Th and U contents of Dog Wash zircons used to distinguish detrital from mixed and metamorphic age domains. Detrital zircons define a maximum depositional age of ca. 1730 Ma, and rims indicate metamorphism before ca. 1636 Ma. This quartzite is thus inferred to be a part of the Paleoproterozoic basement rather than a deformed distal equivalent of the Pinto Mountain Group.

turned quartzite and phyllite correlative with the Big Bear Group are vertical to steeply west dipping and are sandwiched structurally beneath gneisses and above overturned uppermost Stirling Quartzite and stratigraphically higher Cambrian units.

The map pattern of the metasedimentary rocks suggests that the major structural feature of this area is a northeast-vergent, overturned antiform in the hanging wall of the moderately southwest-dipping Doble fault. Big Bear Group quartzite on the overturned limb of the antiform is apparently detached from the underlying core of Early Proterozoic gneisses, since the consistent west-dipping foliation and down dip lineation observed throughout the gneisses (Barth et al. 2000) indicate a lack of basement folding. The Big Bear Group thins northward and becomes more moderately dipping as the antiform is truncated at its northern limit by the Doble fault. Regional relationships and the older on younger geometry of the Doble fault indicate that it originated as a reverse fault in Permo-Triassic time. Northeast of Baldwin Lake, the fault places Early Proterozoic gneiss above overturned Cambrian Wood Canyon Formation and Zabriskie Quartzite. Further to the southeast, apparent displacement on the fault decreases, as the fault cuts down section to place Big Bear Group quartzite above uppermost Stirling Quartzite and Wood Canyon Formation. Small-scale structures and grain-shape preferred orientation in quartzite from both the hanging wall and the footwall of the Doble fault suggest that it was most recently active as a normal fault.

Cameron (1981) suggested that the upper part of the Big Bear Group, west of our study area, contains a ca. 1-km-thick carbonate unit (Green Spot Formation). If Cameron's stratigraphic interpretation is correct, the Green Spot Formation is cut out by the Doble fault. Alternatively, Powell et al. (1983) suggested that the Green Spot Formation is Paleozoic in age; if so, the offset across the southern reach of the Doble fault near Onyx Peak may be negligible. Further stratigraphic and geochemical work on the Green Spot Formation is necessary to resolve its age and stratigraphic position and better constrain the magnitude of offset on the Doble fault.

Structural data thus suggest that quartzite and phyllite of the Big Bear Group originated stratigraphically beneath rocks of the upper Stirling Quartzite and Cambrian units. The lithologic character of this metasedimentary sequence—including a thick, lower quartzite-dominated sequence stratigraphically beneath the Wood Canyon Formation—coupled with the lack of identified Ordovician and Silurian rocks suggests that the San Bernardino Mountains region lay within the craton-miogeocline hinge zone in latest Proterozoic and Paleozoic time (Stewart 1982; Bahde et al. 1997). Stratigraphic sequence, sedimentary structures, and paleocurrent data, however, suggest that the Big Bear Group records a fundamentally differ-

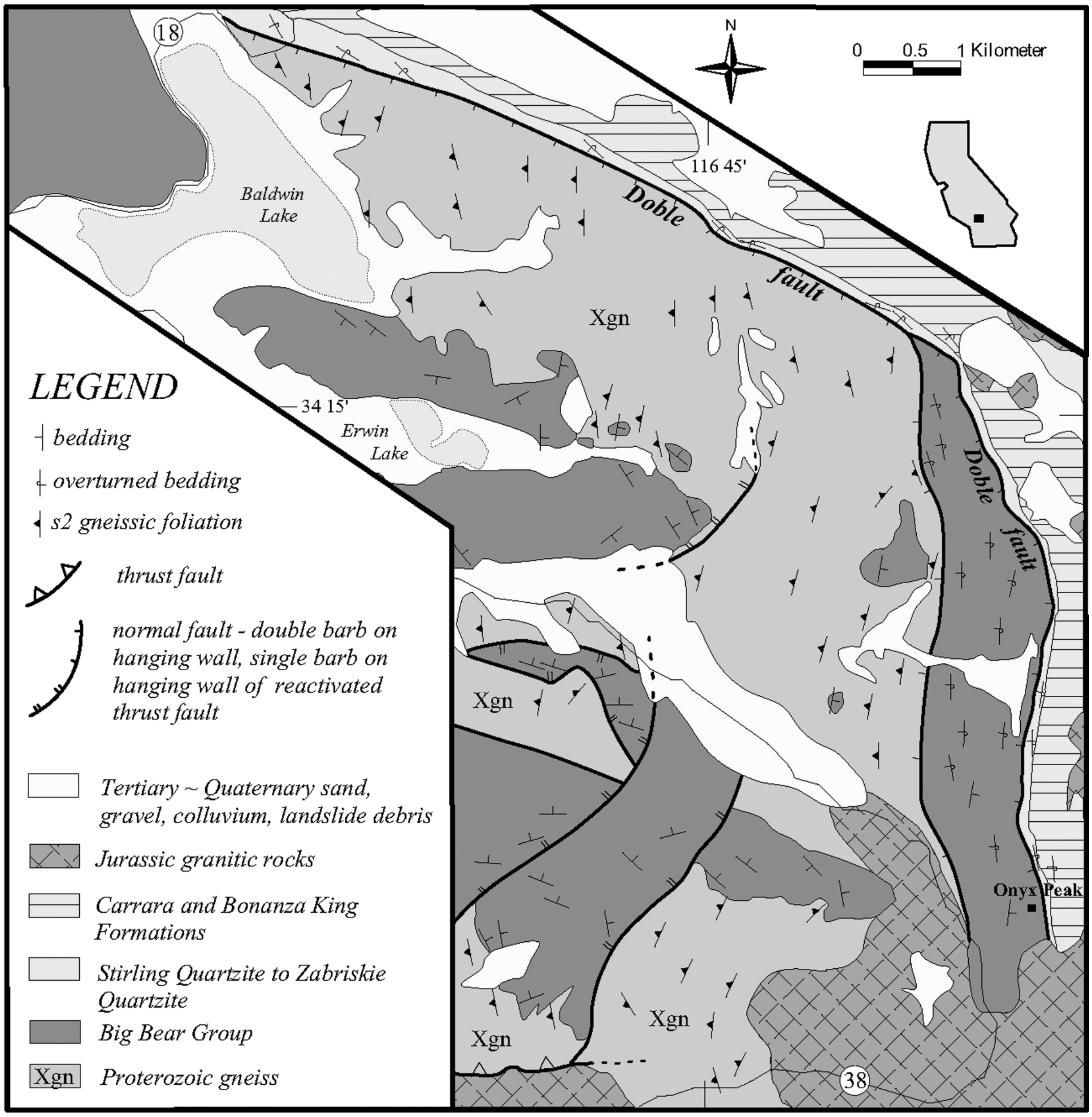

Figure 10. Geologic map of Paleoproterozoic gneiss and Big Gear Group in the Baldwin Lake area, north central San Bernardino Mountains (additional mapping from Cameron 1981). A color version of this figure is available in the online edition of the *Journal of Geology*.

ent siliciclastic depositional setting before onset of miogeoclinal sedimentation. Cameron (1981) inferred a tidal to shallow marine subtidal environment of deposition for the Big Bear Group on the basis of fining-upward ripple laminated beds, mudcracked siltstones, large-scale cross bed sets topped by ripple laminated quartzite recording reversed paleocurrent, and dewatering or animal escape structures. Stewart (2005) inferred an eolian origin for the large-scale cross strata. Large-scale planar tabular and planar wedge cross beds in Big Bear Group quartzite and phyllitic quartzite record paleocurrents toward the north and east, whereas associated small-scale cross strata yield highly variable paleocurrent directions (Barth et al. 1999; Stewart 2005). These north and east paleocurrents are broadly similar to those measured in the Pinto Mountain Group but nearly antipodal to paleocurrent direc-

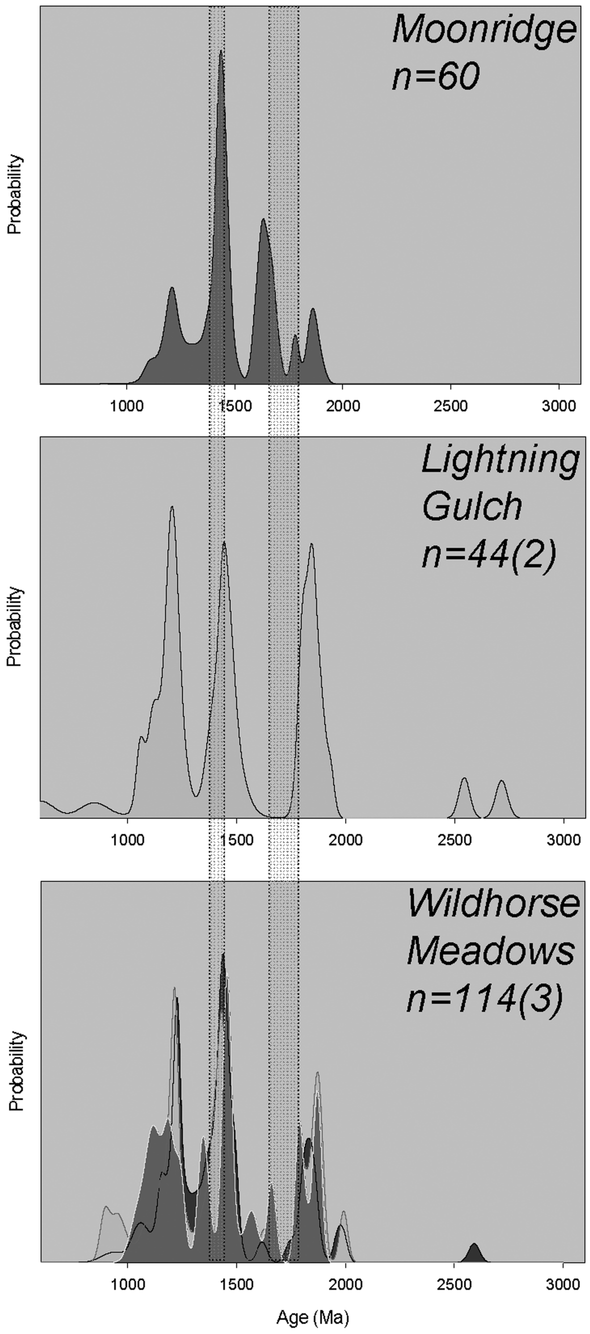

Figure 11. Cumulative probability plot of ages of most concordant detrital zircons from siliciclastic samples of the three formations comprising the Big Bear Group (for sample horizons, see fig. 8). Lightly shaded bars show the range of ages of igneous rocks in the basement of the Mojave province in the Transverse Ranges and southern Mojave Desert. Note the generally poor correspondence of Paleoproterozoic and Mesoproterozoic detrital zircon ages to exposed Mojave basement ages, suggesting derivation of this section from a 1.9–1.8 and 1.5–1.4 Ga basement provenance.

tions recorded in overlying Stirling Quartzite and Wood Canyon Formation, which yield south to southwest paleocurrents typical of miogeoclinal units (Stewart 1982, 2005; Stewart et al. 2001).

Detrital zircons from four samples of quartzite and phyllitic quartzite of the Big Bear Group have three main populations of Proterozoic grains. Two samples from the basal quartzite unit of the Big Bear Group (type lower Wildhorse Meadows Quartzite of Cameron [1981]) yielded a majority of concordant grains, and a third sample yielded a higher proportion of normally discordant grains but similar $^{207}Pb^*/^{206}Pb^*$ ages; here we consider only the concordant subset (114 of 169 grains ≤10% discordant; fig. 11). The majority of detrital zircons are 1900–1150 Ma; the most commonly observed populations are 1893–1785, 1496–1395, and 1257–1148 Ma. Remarkably, grains similar in age to zircons in local or regional Paleoproterozoic basement rocks (1780–1640 Ma) are very rare in these samples, comprising less than 5% of analyzed grains. There is no relationship between grain size, form, or roundness and measured age, so we conclude that there is no relation between age and transport distance or recycling among the observed zircon populations. However, approximately 75% of analyzed grains in the 1496–1395 and 1893–1785 Ma populations are characterized by euhedral to subhedral oscillatory zoning that parallels some or all preserved crystal faces. In contrast, such grains make up only 34% of analyzed grains in the 1257–1148 Ma population, which is predominantly composed of grains with diffuse subhedral to anhedral zonation or lacking in any visible zonation. The youngest concordant grains are 950 ± 30 to 895 ± 22 Ma, providing a maximum depositional age for the basal part of the Big Bear Group that is much younger than we infer for the Pinto Mountain Group.

Three samples from higher siliciclastic parts of the Big Bear Group—two samples from the Lightning Gulch Formation and one from the stratigraphically higher Moonridge quartzite (fig. 11)—yielded mostly concordant and nearly concordant grains as well (102 of 158 grains ≤10% discordant). The youngest concordant grain has a $^{206}Pb^*/^{238}U$ age of 616 ± 9 Ma, suggesting that the middle and upper Big Bear Group is about 625 Ma or younger. The two Lightning Gulch quartzites yielded three main age populations that are identical to those in the underlying Wildhorse Meadows quartzite. However, an additional peak is observed in the Moonridge quartzite, corresponding to detrital zircons with ages of 1786–1640 Ma, grain ages that are very rarely observed in underlying quartzites.

Miogeoclinal Sequence. For purposes of strati-

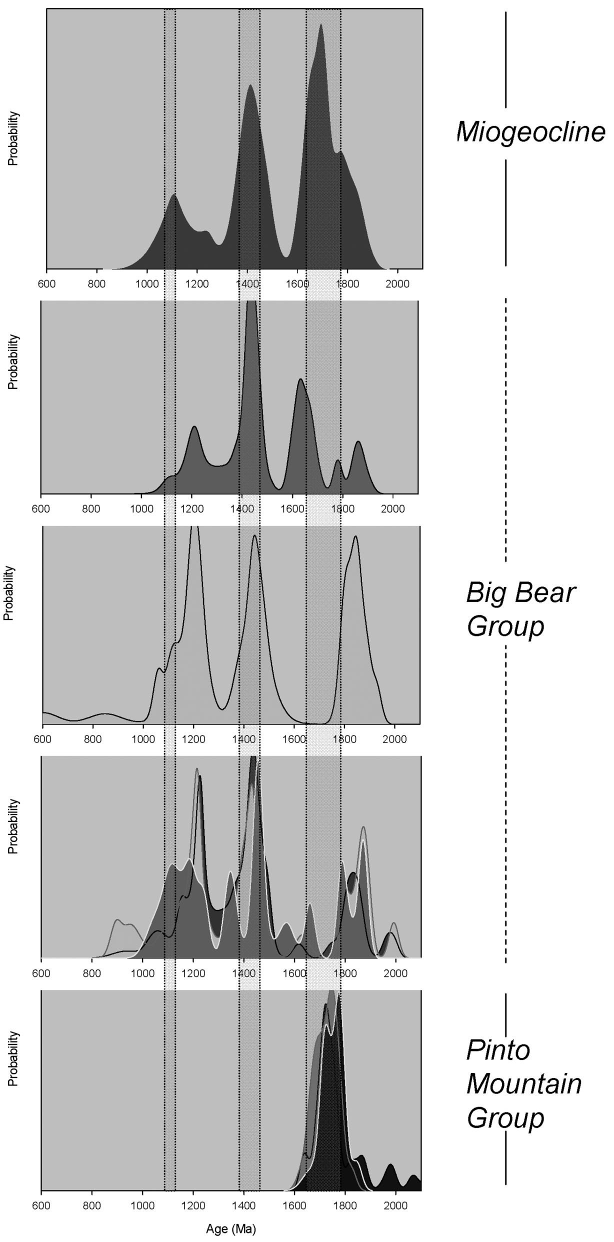

Figure 12. Cumulative probability plot of most concordant zircons from siliciclastic rocks of the Pinto Mountain Group, Big Bear Group, and the Cordilleran miogeocline in inferred time stratigraphic order. Lightly shaded bars show the range of ages of igneous rocks in the local Mojave province basement and, in addition, the ca. 1100 Ma detrital zircon age peak commonly observed in Paleozoic rocks of the Cordilleran miogeocline.

graphic comparison, we analyzed three samples from quartzite in the overlying Neoproterozoic to Cambrian miogeoclinal sequence, one each from the upper Stirling Quartzite, middle member Wood Canyon Formation, and Zabriskie Quartzite (Stewart and Poole 1975). The majority of grains are concordant or slightly normally discordant (153 of 192 grains ≤10% discordant). Most detrital zircons in these samples are between 1900 and 1000 Ma; 12 nearly concordant Archean grains are not plotted but range in age from 3355 to 2451 Ma. Concordant and nearly concordant grains define three main populations with ages of 1787–1626, 1488–1350, and 1185–1055 Ma (fig. 12). These data are consistent with the smaller but more precise TIMS data set of Stewart et al. (2001), who identified predominant 1774 and 1111 Ma populations and discovered four Archean grains between 3121 and 2677 Ma. These observed age populations are thus consistent with predominant age populations observed by Stewart et al. (2001) in a larger sample set of miogeoclinal rocks from throughout the southwestern United States. In miogeocline samples from the San Bernardino Mountains, there is no relationship between grain size, form, or roundness and measured age, so we conclude that there is no relationship between age and transport distance or recycling among the observed zircon populations, nor is the average grain size and roundness significantly different from what we observed in zircons from the Big Bear Group. In addition, microscopic analysis gives no indication that rock type varied in the provenance of the predominant age populations. Approximately 90% of grains preserve euhedral to subhedral oscillatory zoning parallel to some or all crystal faces.

Discussion

Paleoproterozoic metasedimentary and metaigneous rocks record the assembly of Mojave province continental crust between about 1.8 and 1.63 Ga. These basement rocks are locally overlain by remnants of sedimentary sequences of Mesoproterozoic, Neoproterozoic, and Cambrian age, which record sedimentation on stabilized continental crust, and eventual disassembly during formation of the Cordilleran miogeocline in latest Neoproterozoic to Cambrian time.

The initial assembly of materials that formed continental crust in the Mojave province involved accumulation of immature sedimentary rocks on thin, probably oceanic crust, represented by mid-ocean ridge basalt–like amphibolites spatially associated with paragneisses. Amphibolites are enriched relative to likely depleted mantle at 1.8 Ga, and the paragneisses contain abundant older detrital grains, suggesting that the earliest Mojave province crustal rocks accumulated near to an older, rapidly eroding 1.98–1.8 Ga arc terrane that lay to the west or northwest. Our hypothesis is that a sequence of graywacke and shale derived from this adjacent arc terrane was deposited on a mafic basement (oceanic and/or backarc). This thin initial crust comprised the framework rocks for emplacement of 1.79–1.73 Ga early phase arc plutons, and framework rocks were locally metamorphosed during pluton emplacement. Early phase arc plutons in the Mojave province also record interaction with pre-1.8 Ga crust in both premagmatic zircons and bulk rock Nd and Pb isotopic compositions and thus were probably derived from mixing between local enriched mantle and variable proportions of this older Paleoproterozoic source (Wooden et al. 1988; Coleman et al. 2002). The early evolution of the Mojave crustal province thus has close chronologic similarity to the northern Colorado Paleoproterozoic terrane (Premo et al. 2007), including physical mixing of >1.8 Ga detritus, but still relatively primitive plutonic rocks. However, the overall crustal asymmetry suggests that a Hudsonian terrane lay to the northwest or west of the greater Mojave–northern Colorado region.

The end of early phase plutonism at about 1.73 Ga signalled the beginning of a phase of widespread deformation and amphibolite to granulite facies metamorphism between 1.71 and 1.69 Ga. All rocks older than 1.73 Ga are intensely deformed. Only a few remnants of plutonic bodies preserve aspects of their original form and texture. The typical character of these older rocks is one of isoclinally folded and flattened layers with lithologic variations common at the meter or submeter scale. The oldest metamorphic zircon overgrowths yet identified are 1795 Ma, but more commonly metamorphic rims on zircon have ages of 1.71–1.69 Ga, the period of time associated with the Ivanpah Orogeny (Wooden and Miller 1990). Plutonic rocks intruded after 1690 Ma show no evidence of the intense deformation preserved in the older rock packages, and the oldest ages in these younger plutons provide a firm minimum age for the deformation and metamorphism seen in the older rocks. There is now evidence for a granulite grade event at 1795 Ma that affected the graywacke-shale package that was the basement to the older plutonic rocks in the east Mojave and an event of similar significance at 1772 Ma in the west Mojave. Evidence for other metamorphic and deformational between 1795 and 1730 Ma may be found by further analyses of late-forming zircon domains and associated monazite but may in part be lacking because it is obscured by the intensity of the later event(s), so that the older package may be a composite of deformational and metamorphic events in addition to depositional and intrusive events.

Late phase plutonism in the Mojave province between 1.69 and 1.64 Ga was characterized by formation of alkalic, HFSE-enriched rocks having many of the compositional characteristics of A-type granites. This shift in the geochemical character of plutonism likely indicates widespread partial melting of arc basement rocks after 1.69 Ga, based on recent experimental results (e.g., Skjerlie and Johnston 1993; Patiño-Douce 1997, 1999). These observations suggest partial melting of crust thickened during the ca. 1.71–1.69 Ga Ivanpah Orogeny (Wooden and Miller 1990). In this context, late-stage west-vergent deformation between 1.68 and 1.63 Ga is interpreted to record extensional collapse of this thickened arc crust.

The oldest supracrustal sequence deposited on basement, Pinto Mountain Group is an upright, siliciclastic, and carbonate shelf succession with well-preserved sedimentary structures that records the minimum age of stable, normal thickness continental crust in the Mojave province. Detrital zircons are as young as ca. 1630 Ma, providing a maximum depositional age for this succession. No Mesoproterozoic detrital zircons were found in these four samples, yet such zircons are abundant in all Neoproterozoic and Paleozoic siliciclastic sedimentary rocks in this region (e.g., Stewart et al. 2001), including the Neoproterozoic Big Bear Group and latest Neoproterozoic to Cambrian miogeoclinal rocks exposed immediately to the northwest. This observation indicates that the Pinto Mountain Group was probably deposited between 1.63 and 1.45 Ga. This inference suggests that the Pinto Mountain Group is correlative to Cordilleran Proterozoic succession A and is therefore the approximate temporal equivalent of Wernecke, Belt, and Muskwa supergroups of the northern Cordillera (Link et al. 1993), and it was deposited earlier than the Apache Group and Grand Canyon Supergroup of western Arizona and the Pahrump Group of eastern California (Timmons et al. 2001; fig. 13). Recent geochronologic results suggest the Pinto Mountain Group is younger than intraarc basin quartzite of the Mazatzal Group and similar in age or younger than the Chino Valley and Hess Canyon Group quartzites (Cox et al. 2002). Thus, the Pinto Mountain Group may be a remnant of a somewhat more widespread post-Mazatzal Orogeny shelf sequence.

Detrital and metamorphic zircons in the Dog

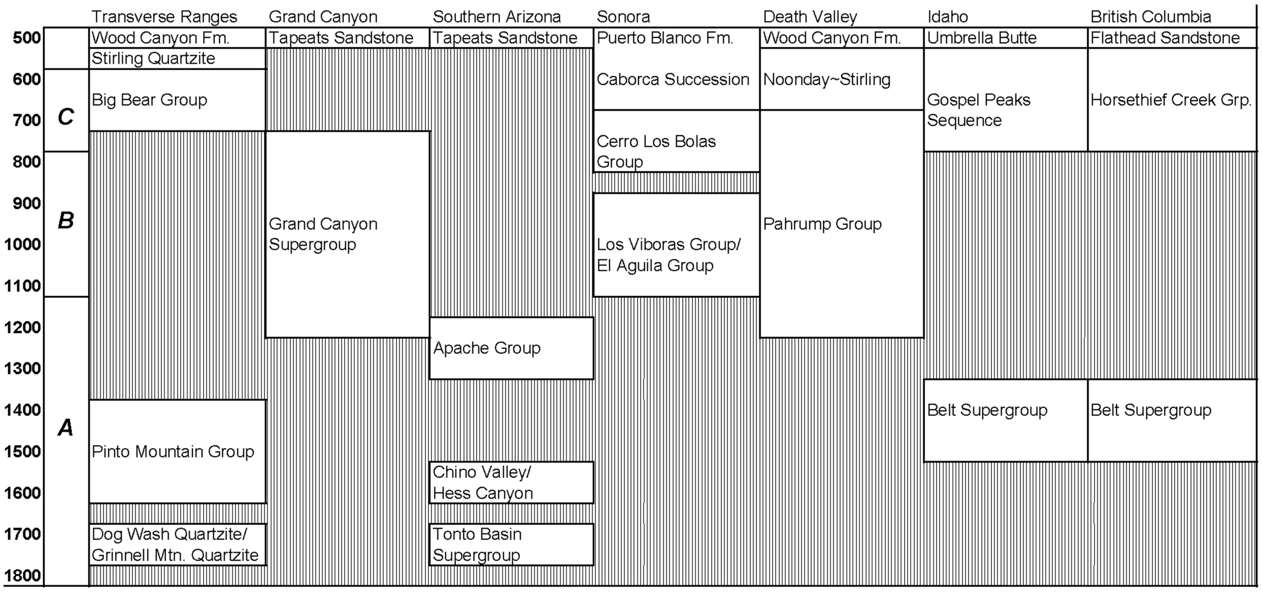

Figure 13. Regional stratigraphic correlation chart for Proterozoic sedimentary rocks in the southwestern Cordillera, illustrating the inferred correlation of quartzite sequences in this study (adapted from Link et al. 1993; additional data from Timmons et al. 2001; Cox et al. 2002; Stewart et al. 2002; Lund et al. 2003). Grinnell Mountain and Dog Wash quartzites are components of the Paleoproterozoic basement and are not representative of a regionally widespread Joshua Tree terrane. Pinto Mountain Group is correlated with Cordilleran Proterozoic succession A and is therefore similar in age or slightly younger than quartzites of the Mazatzal Group of the Tonto Basin Supergroup. Big Bear Group is pre–Stirling Quartzite in age and correlated with the early part of succession C deposited in the earliest stages of Neoproterozoic Cordilleran rifting.

Wash quartzite indicate that quartzite-bearing metasedimentary rock sequences to the west of the type section are not correlative with the Pinto Mountain Group. This observation significantly reduces the areal extent and significance of the Joshua Tree terrane of Powell (1981) but is consistent with the definition of the more diminutive Placer Mountain assemblage of Powell (1993). We conclude that the Pinto Mountain Group is an early postorogenic shallow shelf sedimentary succession deposited on west Mojave province crust, coincident with but unrelated to the rift that initiated the Cordilleran miogeocline in this region.

Structural and stratigraphic evidence suggests that the Big Bear Group is distinctly younger than the Pinto Mountain Group yet older and deposited in a different tectonic setting than the Neoproterozoic-Cambrian miogeoclinal sequence (Stirling Quartzite and higher units) that overlies it. Paleocurrent data suggest that siliciclastic sediment was transported north and northeastward during Big Bear Group deposition but southwestward, off the established west-facing Cordilleran continental shelf, by upper Stirling and Wood Canyon time. Detrital zircon data indicate that the shift in paleocurrent directions, although not accompanied by a recognizable shift in transport distance or degree of recycling, was accompanied by a shift in the geochronologic and possibly the lithologic character of siliciclastic sediment provenance. We therefore propose that the older Big Bear Group records a different depositional setting than the Stirling and younger miogeoclinal units in this region. Stewart et al. (2002) suggested a correlation with Cordilleran Proterozoic succession B, their Neoproterozoic Rodinian epicontinental sequence. However, if further work confirms that much of the Big Bear Group is younger than 625 Ma yet pre-Stirling in age, a correlation with the early part of succession C and a tectonic setting in the earliest stages of Cordilleran Neoproterozoic rifting seems more likely (fig. 13).

The paleocurrent and detrital zircon age data reported here can help to define the location and geologic character of the provenance of these sedimentary sequences. As discussed by Stewart et al. (2001), most age populations of detrital zircons in miogeoclinal rocks (3.4–2.3, 1.8–1.6, 1.45–1.40, and 1.2–1.0 Ga) can be matched to observed basement rocks, suggesting a western North American basement provenance (Gehrels et al. 1995; Gehrels and Stewart 1998). The problematic exception is the widespread occurrence of 1.2–1.0 Ga grains, for which Stewart et al. (2001) hypothesized a source in silicic volcanic fields now largely buried and/or destroyed by erosion. Our results support this interpretation, since the older Proterozoic populations in the miogeoclinal samples from the San Bernardino Mountains are very good matches for zircons in orthogneisses and granitic rocks that characterize Proterozoic basement rock in this region (Anderson and Bender 1989; Wooden and Miller 1990; Barth et al. 2000), and the 1200–1000 Ma population is dominated by 80–360-μm subhedral to euhedral oscillatory-zoned zircons, which we suggest are likely to have been derived from granitic or felsic volcanic rocks.

In contrast, only one of the three predominant age populations in the older Big Bear Group can be convincingly matched to observed western North America basement rocks. Predominant Early Proterozoic basement rocks range in age from about 1790 to 1640 Ma (e.g., Wooden and Miller 1990; Karlstrom and Bowring 1991; Barth et al. 2000; Duebendorfer et al. 2001; this study), with rare older rocks and older zircon grains found as xenocrysts in orthogneisses and detrital grains in paragneisses (Wooden et al. 1994; Hawkins et al. 1996; Barth et al. 2000). This age range provides a very good fit to Early Proterozoic detrital grains found in Cambrian miogeoclinal strata (Gehrels et al. 1995; Stewart et al. 2001; this study) but is a very poor fit for the 1893–1785 Ma population in the lower and middle parts of the Big Bear Group. The 1185–1055 Ma zircons of uncertain provenance that dominate many Cambrian southern miogeoclinal samples (Gehrels et al. 1995; Stewart et al. 2001) including the three miogeoclinal samples described here are similarly a poor match to the 1257–1148 Ma population in the Big Bear Group. These data suggest that either (1) the relative proportions of rock types changed significantly during progressive erosion of a single provenance that fed both sequences or (2) these two sequences bracket a fundamental provenance shift. The former is difficult to rigorously evaluate, given the limited exposure of Proterozoic basement rocks. The later hypothesis is consistent with paleocurrent data suggesting that the provenance of the Big Bear Group lay southwest of the final Cordilleran rift.

The detrital zircon provenance signature of siliciclastic sediment in the Big Bear Group mimics and expands upon the characterization described earlier of older crust that lay to the northwest and west of southern California during initial formation of the Mojave province. The lack of correlation between grain age and crystal size or roundness suggests that all three major detrital zircon age populations were derived from crystalline rocks exposed in proximity to one another. The predominance of oscillatory-zoned grains in the 1496–1395 and 1893–1785 Ma populations suggests that the provenance contained igneous rocks of this age and/or orthogneisses whose protoliths were of this age. In contrast, the predominance of weakly zoned or unzoned grains, some with preserved anhedral overgrowths, suggests that the 1257–1148 Ma population was derived from an orogenic belt characterized by high-grade metamorphism and zircon growth at this time. If these sources were indeed in relatively close proximity, zircons in the Big Bear Group record derivation from a late Mesoproterozoic orogenic belt that incorporated and partially reworked older Paleoproterozoic to Mesoproterozoic igneous rocks. The older Paleoproterozoic component of this orogenic belt is of the same chronologic character as rocks we infer lay in this position in Paleoproterozoic time and contributed detritus to the original assembly of Mojave province crust. This orogenic belt lay west of the southwestern Laurentian margin until very late Neoproterozoic time, suggesting that ultimate rifting of Mojave province crust and establishment of the Cordilleran miogeocline at this latitude were not completed until 0.62–0.55 Ga.

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REFERENCES CITED

Anderson, J. L., and Bender, E. E. 1989. Nature and origin of Proterozoic A-type granitic magmatism in the southwestern United States of America. Lithos 23:19–52.

Bahde, J.; Barreta, C.; Cederstrand, L.; Flaugher, M.; Heller, R.; Irwin, M.; Swartz, C.; Traub, S.; Cooper, J.; and Fedo, C. 1997. Neoproterozoic–Lower Cambrian sequence stratigraphy, eastern Mojave Desert, California: implications for base of the Sauk Sequence, craton-margin hinge zone, and evolution of the Cordilleran continental margin. *In* Girty, G. H.; Hanson, R. E.; and Cooper, J. D., eds. Geology of the Western Cordillera: perspectives from undergraduate research. Pac. Sect., Soc. Econ. Paleontol. Mineral., p. 1–19.

Barth, A. P.; Potter, M.; Wooden, J. L.; Stewart, J. H.; and Coleman, D. S. 1999. Detrital zircon geochronology of Proterozoic quartzites from the western Mojave province. Geol. Soc. Am. Abstr. Program 31:299.

Barth, A. P.; Wooden, J. L.; Coleman, D. S.; and Fanning, C. M. 2000. Geochronology of the Proterozoic basement of southwesternmost North America, and the origin and evolution of the Mojave crustal province. Tectonics 19:616–629.

Bender, E. E.; Morrison, J.; Anderson, J. L.; and Wooden, J. L. 1993. Early Proterozoic ties between two suspect terranes and the Mojave crustal block of the southwestern U.S. J. Geol. 101:715–728.

Bennett, V. C., and DePaolo, D. J. 1987. Proterozoic crustal history of the western United States as determined by neodymium isotopic mapping. Geol. Soc. Am. Bull. 99:674–685.

Bond, G. C.; Christie-Blick, N.; Kominz, M. A.; and Devlin, W. J. 1985. An early Cambrian rift to post-rift transition in the Cordillera of western North America. Nature 315:742–746.

Brown, H. J. 1991. Stratigraphy and paleogeographic setting of Paleozoic rocks in the San Bernardino Mountains, California. *In* Cooper, J. D., and Stevens, C. H., eds. Paleozoic paleogeography of the western United States. Pac. Sect., Soc. Econ. Paleontol. Mineral., p. 193–207.

Cameron, C. S. 1981. Geology of the Sugarloaf and Delamar Mountain areas, San Bernardino Mountains, California. PhD dissertation, Massachusetts Institute of Technology, Cambridge.

Coleman, D. S.; Barth, A. P.; and Wooden, J. L. 2002. Early to Middle Proterozoic construction of the Mojave province, southwestern United States. Gondwana Res. 5:75–78.

Coleman, D. S.; Wooden, J. L.; and Barth, A. P. 1999. The origin of mixed-province isotopic signatures: an example from the Proterozoic Mojave province. Geol. Soc. Am. Abstr. Programs 31:260.

Corsetti, F. A., and Hagadorn, J. W. 2000. Precambrian-Cambrian transition: Death Valley, United States. Geology 28:299–302.

Cox, R.; Martin, M. W.; Comstock, J. C.; Dickerson, L. S.; Ekstrom, I. L., and Sammons, J. H. 2002. Sedimentology, stratigraphy, and geochronology of the Proterozoic Mazatzal Group, central Arizona. Geol. Soc. Am. Bull. 114:1535–1549.

Dibblee, T. W. 1982. Geology of the San Bernardino Mountains, southern California. *In* Fife, D. F., and Minch, J. A., eds. Geology and mineral wealth of the California Transverse Ranges. Santa Ana, CA, S. Coast Geol. Soc., p. 149–169.

Duebendorfer, E. M.; Chamberlain, K. R.; and Jones, C. S. 2001. Paleoproterozoic tectonic history of the Cerbat Mountains, northwestern Arizona: implications for crustal assembly in the southwestern United States. Geol. Soc. Am. Bull. 113:575–590.

Flodin, E. A.; Wooden, J. L.; Miller, D. M.; Barth, A. P.; and Bone, J. D. 1997. Petrogenesis of Early Proterozoic granitic and meta-granitic rocks of the Mojave crustal province, southern California. Geol. Soc. Am. Abstr. Programs 29:13.

Gehrels, G. E.; Dickinson, W. R.; Ross, G. M.; Stewart, J. H.; and Howell, D. G. 1995. Detrital zircon reference for Cambrian to Triassic miogeoclinal strata of western North America. Geology 23:831–834.

Gehrels, G. E., and Stewart, J. H. 1998. Detrital zircon U-Pb geochronology of Cambrian to Triassic miogeoclinal and eugeoclinal strata of Sonora, Mexico. J. Geophys. Res. 103:2471–2487.

Hart, S. R.; Blusztajn, J.; Dick, H. J. B.; Meyer, P. S.; and Muehlenbachs, K. 1999. The fingerprint of seawater circulation in a 500-meter section of ocean crust gabbro. Geochim. Cosmochim. Acta 63:4059–4080.

Hawkins, D. P.; Bowring, S. A.; Ilg, B. R.; Karlstrom, K. E.; and Williams, M. L. 1996. U-Pb geochronologic constraints on the Paleoproterozoic crustal evolution of the Upper Granite Gorge, Grand Canyon, Arizona. Geol. Soc. Am. Bull. 108:1167–1181.

Hoffman, P. F. 1988. United plates of America. Annu. Rev. Earth Planet. Sci. 16:543–603.

Karlstrom, K. E., and S. A. Bowring. 1991. Styles and timing of Early Proterozoic deformation in Arizona: constraints on tectonic models. Ariz. Geol. Soc. Dig. 19:1–10.

Karlstrom, K. E.; Harlan, S. S.; Williams, M. L.; McLelland, J.; Geissman, J. W.; and Ahall, K. I. 1999. Refining Rodinia. Geol. Soc. Am. Today 9:1–7.

Link, P. K.; Christie-Blick, N.; Devlin, W. J.; Elston, D. P.; Horodyski, R. J.; Levy, M.; Miller, J. M. G.; et al. 1993. Middle and Late Proterozoic stratified rocks of the western U.S. Cordillera, Colorado Plateau, and Basin and Range province. *In* Reed, J. C., Jr.; Houston, M. E.; Houston, R. S.; Link, P. K.; Rankin, D. W.; Sims, P. K.; and Van Schmus, W. R., eds. Precambrian: conterminous U.S. (Geology of North America, Vol. C-2). Boulder, CO, Geol. Soc. Am., p. 463–595.

Lund, K.; Aleinikoff, J. N.; Evans, K. V.; and Fanning, C. M. 2003. SHRIMP U-Pb geochronology of Neoproterozoic Windermere Supergroup, central Idaho: implications for rifting of western Laurentia and synchroneity of Sturtian glacial deposits. Geol. Soc. Am. Bull. 115:349–372.

Miller, D. M., and Wooden, J. L. 1992. Proterozoic geology of the New York, Ivanpah, and Providence mountains, California: field guide. U.S. Geol. Surv. Open File Rep. 92–000, 21 p.

Patiño-Douce, A. E. 1997. Generation of metaluminous

A-type granites by low-pressure melting of calc-alkaline granitoids. Geology 25:743–746.

———. 1999. What do experiments tell us about the relative contributions of crust and mantle to the origin of granitic magmas? Geol. Soc. Lond. Spec. Publ. 168: 55–75.

Powell, R. E. 1981. Geology of the crystalline basement complex, eastern Transverse Ranges, southern California. PhD dissertation, California Institute of Technology, Pasadena.

———. 1993. Balanced palinspastic reconstruction of prelate Cenozoic paleogeology, southern California: geologic and kinematic constraints on evolution of the San Andreas fault system. *In* Powell, R. E.; Weldon, R. J.; and Matti, J. C., eds. The San Andreas fault system. Geol. Soc. Am. Mem. 178:1–106.

Powell, R. E.; Matti, J. C.; Cox, B. F.; Oliver, H. W.; Wagini, A.; and Campbell, H. W. 1983. Mineral resource potential of the Sugarloaf roadless area, San Bernardino County, California. U.S. Geol. Surv. Map MF-1606-A.

Premo, W. R.; Kellogg, K.; and Bryant, B. 2007. SHRIMP U-Pb zircon ages for Paleoproterozoic basement rocks from the northern and central Colorado front range: a refinement of the timing of crustal growth in the Colorado province. Geol. Soc. Am. Abstr. Program 39: 221.

Rämö, O. T., and Calzia, J. P. 1998. Nd isotopic composition of cratonic rocks in southern Death Valley: evidence for a substantial Archean source component in Mojavia. Geology 26:891–894.

Signor, P. W., and Mount, J. F. 1989. Paleontology of the Lower Cambrian Waucoban Series in eastern California and western Nevada. *In* Christie-Blick, N., and Levy, M., eds. Late Proterozoic and Cambrian tectonics, sedimentation, and record of metazoan radiation in the western United States. Field Trip Guidebook T331. Washington, DC, Am. Geophys. Union, p. 47–53.

Skjerlie, K. P., and Johnston, A. D. 1993. Fluid-absent melting behavior of an F-rich tonalitic gneiss at mid-crustal pressures: implications for the generation of anorogenic granites. J. Petrol. 34:785–815.

Stewart, J. H. 1972. Initial deposits of the Cordilleran geosyncline: evidence of a late Precambrian (<850 m.y.) continental separation. Geol. Soc. Am. Bull. 83: 1345–1360.

———. 1982. Regional relations of Proterozoic Z and Lower Cambrian rocks in the western United States and northern Mexico. *In* Cooper, J. D., ed. Geology of selected areas in the San Bernardino Mountains, western Mojave Desert, and southern Great Basin, California. Shoshone, CA, Death Valley, p. 171–186.

———. 2005. Eolian deposits in the Neoproterozoic Big Bear Group, San Bernardino Mountains, California, USA. Earth Sci. Rev. 73:47–62.

Stewart, J. H.; Amaya-Martinez, R.; and Palmer, A. R. 2002. Proterozoic and Cambrian strata of Sonora, Mexico: Rodinian supercontinent to Laurentian Cordilleran margin. Geol. Soc. Am. Spec. Pap. 365:5–48.

Stewart, J. H.; Gehrels, G. E.; Barth, A. P.; Link, P. K.; Christie-Blick, N.; and Wrucke, C. T. 2001. Detrital zircon provenance of Mesoproterozoic to Cambrian arenites in the western United States and northwestern Mexico. Geol. Soc. Am. Bull. 113:1343–1356.

Stewart, J. H., and Poole, F. G. 1975. Extension of the Cordilleran miogeosynclinal belt to the San Andreas fault, southern California. Geol. Soc. Am. Bull. 86: 205–212.

Timmons, J. M.; Karlstrom, K. E.; Dehler, C. M.; Geissman, J. W.; and Heizler, M. T. 2001. Proterozoic multistage (ca. 1.1 and 0.8 Ga) extension recorded in the Grand Canyon Supergroup and establishment of northwest- and north-trending tectonic grains in the southwestern United States. Geol. Soc. Am. Bull. 113: 163–181.

Wooden, J. L., and Miller, D. M. 1990. Chronologic and isotopic framework for Early Proterozoic crustal evolution in the eastern Mojave Desert region, SE California. J. Geophys. Res. 95:20,133–20,146.

Wooden, J. L.; Nutman, A. P.; Miller, D. M.; Howard, K. A.; Bryant, B.; DeWitt, E.; and Mueller, P. A. 1994. SHRIMP U-Pb zircon evidence for Late Archean and Early Proterozoic crustal evolution in the Mojave and Arizona crustal provinces. Geol. Soc. Am. Abstr. Program 26:69.

Wooden, J. L.; Stacey, J. S.; Howard; K. A.; Doe, B. R.; and Miller, D. M. 1988. Pb isotopic evidence for the formation of Proterozoic crust in the southwestern United States. *In* Ernst, W. G., ed. Metamorphism and crustal evolution of the western United States. Englewood Cliffs, NJ, Prentice Hall, p. 68–86.