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# Geochronology of the Proterozoic basement of southwesternmost North America, and the origin and evolution of the Mojave crustal province

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**Abstract.** The Proterozoic Baldwin gneiss in the central Transverse Ranges of southern California, a part of the Mojave crustal province, is composed of quartzofeldspathic gneiss and schist, augen and granitic gneiss, trondhjemite gneiss, and minor quartzite, amphibolite, metagabbro, and metapyroxenite. Sensitive high resolution ion microprobe (SHRIMP) data indicate that augen and granitic gneisses comprise a magmatic arc intrusive suite emplaced between 1783 ± 12 and 1675 ± 19 Ma, adjacent to or through thinned Archean crust. High U/Th rims on zircons in most samples suggest an early metamorphic event at ~1741 Ma, but peak amphibolite facies metamorphism and penetrative, west vergent deformation occurred after 1675 Ma. The Baldwin gneiss is part of a regional allochthon emplaced by west vergent deformation over a Proterozoic shelf-slope sequence (Joshua Tree terrane). We hypothesize that emplacement of this regional allochthon occurred during a late Early or Middle Proterozoic arc-continent collision along the western margin of Laurentia.

## 1. Introduction

The origin of the Mojave crustal province of the southwestern United States is significant for geochemical models of Late Archean-Early Proterozoic evolution of the North American craton and for reconstructions of the configuration of the Late Proterozoic supercontinent. The North American craton was assembled from several Archean nuclei welded by Proterozoic orogenic belts (Figure 1). It is unclear what physical processes dominated the joining of these nuclei and subsequent growth of the amalgamated craton; both continuous and episodic models for Late Archean and Proterozoic growth of the craton have been proposed [*Patchett and Arndt*, 1986; *Bowring and Podosek*, 1989; *Hoffman*, 1989]. A significant uncertainty in these models is the origin of several regions of the craton (Wopmay, Penokean, and Mojave provinces) within which rocks have 2.0 - 2.4 Ga Nd model ages that are significantly older than their crystallization ages. The origin of these model ages is central to geochemical models for crustal growth.

The North American craton was part of a larger Late Proterozoic supercontinent, Rodinia [*McMenamin and McMenamin*, 1990] (Figure 1), for which the organization and plate tectonic evolution are uncertain (see review of palinspastic models by *Karlstrom et al.*, [1999]). Identification of the conjugate rift pair for western North America, removed during the formation of the Cordilleran miogeocline, is critical to development of these models. Because the Mojave crustal province extended to the southwestern North American continental shelf edge at the time of rifting [*Wooden and Miller*, 1990; *Barth et al.*, 1995], its crustal history and correlation with Precambrian basement rocks in Asia, Australia, and east Antarctica provide key constraints on plate reconstructions.

In this paper, we begin to address these issues with new mapping and geochronologic data from the San Bernardino Mountains of southern California. Their position at the western edge of the Mojave province (Figures 1 and 2) make the San Bernardino Mountains an ideal location to investigate what lay outboard of Laurentia prior to rifting. Our hypothesis is that the central San Bernardino Mountains expose an Early Proterozoic plutonic arc, intruded into continental slope and basinal metasedimentary rocks, and that this arc and its framework rocks were metamorphosed and deformed by west vergent thrusting over an Archean-Early Proterozoic continental margin that lay to the west.

## 2. Geologic Setting

### 2.1. Proterozoic Crustal Provinces of the Southwesternmost North American Craton

Proterozoic basement rocks in Nevada, Arizona, and southern California, part of the inner accretionary and outer tectonic belts of *Van Schmus et al.* [1993], are divided into the Yavapai, Mazatzal, and Mojave crustal provinces [*Condie*, 1982; *Karlstrom et al.*, 1987; *Karlstrom and Bowring*, 1988; *Wooden and Miller*, 1990]. Although the boundaries between these provinces are diffuse, the northern Yavapai province is composed mostly of rocks older than 1.7 Ga, whereas few rocks older than 1.7 Ga are known in the Mazatzal province (all ages quoted herein are based on the revised decay constants of *Steiger and Jager* [1977]). The Yavapai province also contains a higher (though still small) proportion of recycled crustal material than the Mazatzal. In contrast, the Mojave province underwent a 1.7 Ga orogenic event but retains geochemical evidence for an older Proterozoic and Archean heritage.

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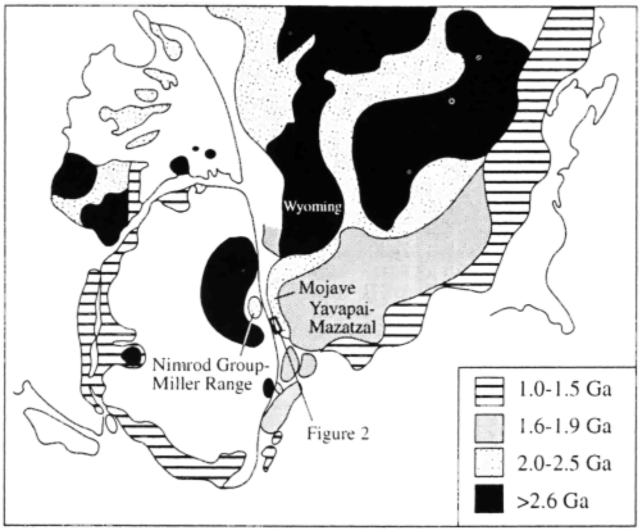

**Figure 1.** Crust formation age provinces of the North American craton and possible adjacent cratons prior to Late Proterozoic rifting of Rodinia and formation of the Cordilleran miogeocline (adapted from *Borg and DePaolo* [1994]). Rectangle shows the study area in the Transverse ranges, in the westernmost Mojave Province of Laurentia on the shoulder of the Cordilleran rifted margin.

Proterozoic basement rocks in westernmost Arizona, southern Nevada, and southeastern California are geochemically distinct from the Mazatzal and Yavapai provinces and are termed the Mojave crustal province [*Bennett and DePaolo*, 1987; *Wooden et al.*, 1988]. In the eastern Mojave province the oldest recognized rocks include the 1840 Ma Elves Chasm pluton in the Grand Canyon [*Hawkins et al.*, 1996], quartzofeldspathic gneisses and amphibolite, metamorphosed at low pressure in the granulite facies [*Thomas et al.*, 1988; *Young et al.*, 1989; *Hawkins et al.*, 1996]. Geochemistry and Pb isotopic systematics in zircon suggest that the protoliths of the gneissic rocks were either a volcanic/immature sedimentary protolith sequence older than 1.8 Ga, mature sediments derived from a cratonal source older than 1.8 Ga, or some combination of these; the structural relationship of the Elves Chasm pluton to surrounding rocks is unknown. The gneisses are intruded by metaplutonic rocks ranging from 1760 to1710 Ma [*DeWitt et al.*, 1984; *Wooden and Miller*, 1990; *Hawkins et al.*, 1996]. These plutons provide a maximum age limit on the principal orogenic event in this region, informally termed the Ivanpah orogeny, dated at 1705-1696 Ma by U-Pb sphene and monazite. This event is temporally correlative with, though higher grade than the equivalent event in Arizona, the 1.71-1.68 Ga Yavapai orogeny [*Karlstrom and Bowring*, 1991; *Ilg et al.*, 1996]. Postorogenic, potassic granitic rocks [*Bender et al.*, 1990; *Anderson and Morrison*, 1992] range in age from 1690 to1640 Ma. As in Arizona, rocks in the Mojave province are intruded by 1.38-1.45 Ga granites and 1.1 Ga diabase dikes [*Anderson and Bender*, 1989; *Hammond*, 1986; *Heaman and Grotzinger*, 1992; *Martin and Walker*, 1992].

The Mojave crustal province is recognized by distinctive Nd and Pb isotopic signatures [*Bennett and DePaolo*, 1987; *Wooden et al.*, 1988; *Wooden and Miller*, 1990; *Wooden and DeWitt*, 1991]. Depleted mantle Nd model ages are 2.0-2.3 Ga for granitic rocks with crystallization ages of 1.7 and 1.4 Ga, and Pb isotope ratios yield higher $^{207}$Pb/$^{204}$Pb for a given value of $^{206}$Pb/$^{204}$Pb compared to Arizona. Mojave province crust thus includes significant recycled Archean-Early Proterozoic material with low Sm/Nd and high U/Pb and Th/Pb, similar to the Penokean province of the Great Lakes region [*Nelson and DePaolo*, 1984; *Patchett and Arndt*, 1986; *Barovich et al.*,

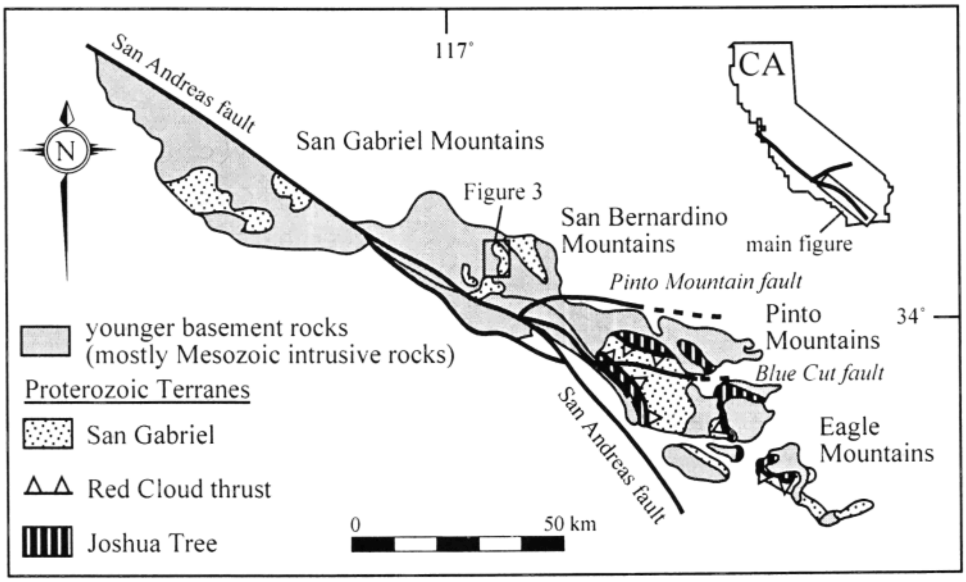

**Figure 2.** Proterozoic geology of the Transverse Ranges, with the San Bernardino Mountains study area highlighted. Proterozoic rocks in the San Bernardino Mountains comprise part of the regional Proterozoic San Gabriel allochthon, a long-lived Early Proterozoic arc terrane emplaced along the west vergent Red Cloud thrust atop (para)autochthonous granitic basement and shelf and slope metasedimentary rocks of Joshua Tree terrane [*Powell*, 1993].

1989] and the Wopmay orogen of northwest Canada [*Bowring and Podosek*, 1989]. The Mojave province lies at the western edge of the North American craton, so Proterozoic plate reconstructions are highly dependent on the inferred source for this older component. Because the source of the zircon and isotopic signatures was apparently not the Wyoming Province [*Wooden and DeWitt*, 1991; *Wooden et al.*, 1994; *Mueller et al.*, 1992, 1994], compatible isotopic and age provinces must be identified in Siberia [*Sears and Price*, 1978], Antarctica [*Dalziel*, 1991; *Hoffman*, 1991; *Moores*, 1991; *Borg and DePaolo*, 1994], or Australia [*Ross et al.*, 1992; *Karlstrom et al.*, 1999].

### 2.2. Tectonostratigraphic Setting of the Western Mojave Province

The Mojave crustal province extends southwestward to the late Precambrian shelf edge in the Transverse Ranges of southern California [*Martin and Walker*, 1992; *Barth*, 1990; *Barth et al.*, 1993, 1995]. *Powell* [1981, 1993] and *Silver* [1982] recognized two Proterozoic basement terranes in the Transverse Ranges: the San Gabriel and Joshua Tree terranes (Figure 2). Precambrian rocks in the central San Bernardino Mountains are autochthonous North American craton overlain by Late Proterozoic-Paleozoic strata of the Cordilleran miogeocline [*Stewart and Poole*, 1975; *Powell*, 1993]. San Gabriel and Joshua Tree terranes were formerly considered to be allochthonous to this part of North America [e.g., *Powell*, 1981; *Reed*, 1993]. However, many workers have shown that Precambrian basement in the San Gabriel terrane is isotopically part of the Mojave crustal province [*Bennett and DePaolo*, 1987; *Bender et al.*, 1993; *Barth et al.* 1995], and *Powell* [1993] correlated Precambrian gneisses in the central San Bernardino Mountains with San Gabriel terrane. Very few data are available to characterize Joshua Tree terrane, which appears isotopically similar to the Mojave province [*Bennett and DePaolo*, 1987; *Bender et al.*, 1993]. In the discussion that follows, we use these correlations to develop a testable hypothesis that relates these terranes to one another in a tectonic model for the Proterozoic evolution of the Mojave crustal province.

The structurally lowest Precambrian rocks comprise Joshua Tree terrane (equivalent to the Joshua Tree and Placer Canyon suites of *Powell* [1993]), including ~1.7 Ga granitic rocks and an unconformably overlying shelf-slope assemblage of metasedimentary rocks including quartzite and calcitic and dolomitic marble [*Powell*, 1981]. Joshua Tree terrane is structurally overlain by San Gabriel terrane (equivalent to the Pinkham Canyon and Monument Mountain suites of *Powell* [1993]), which includes metaigneous and pelitic metasedimentary rocks intruded by ~1.7 Ga granitic rocks and the 1189 Ma San Gabriel anorthosite-jotunite-syenite complex [*Barth et al.*, 1995].

The San Gabriel and Joshua Tree terranes are juxtaposed along the Red Cloud thrust. The timing of motion and vergence of the Red Cloud thrust fault are uncertain, and the thrust zone itself is likely to be polygenetic [*Powell*, 1981; *Postlethwaite*, 1988]. Regional map patterns and fold asymmetry suggest the earliest juxtaposition of these two terranes occurred by west vergent overthrusting of San Gabriel terrane above shelf-slope sediments of Joshua Tree terrane, prior to intrusion of the San Gabriel anorthosite-jotunite-syenite complex [*Powell*, 1993].

### 2.3. Geology of Precambrian Rocks in the San Bernardino Mountains

Precambrian gneisses in the San Bernardino Mountains were first described in the vicinity of Baldwin Lake in the northcentral part of the range and named Baldwin gneiss [*Guillou*, 1953]. Baldwin gneiss was mapped and briefly described by *Dibblee* [1964a,b, 1967a,b], and lithologic subdivisions were suggested by *McJunkin* [1976] and *Butters* [1981]. Stratigraphic and structural relations indicate the gneisses are pre-latest Proterozoic. *Silver* [1971] reported a U-Pb age of ~1730 Ma for "plutons" intrusive into gneisses; the locality and lithologic unit sampled are unknown. Potentially correlative gneisses were mapped in the eastern and southcentral parts of the range [*Morton et al.*, 1980; *Matti et al.*, 1982].

Baldwin gneiss is composed of biotite +/- muscovite, aluminum silicate, and garnet quartzofeldspathic gneiss and schist, quartzite, amphibolite, metagabbro, metapyroxenite, augen gneiss, and biotite +/- muscovite granite and trondhjemite gneiss (Figure 3). These rock types are interlayered at meter to decimeter scale, with compositional banding dipping moderately west. The geologic map

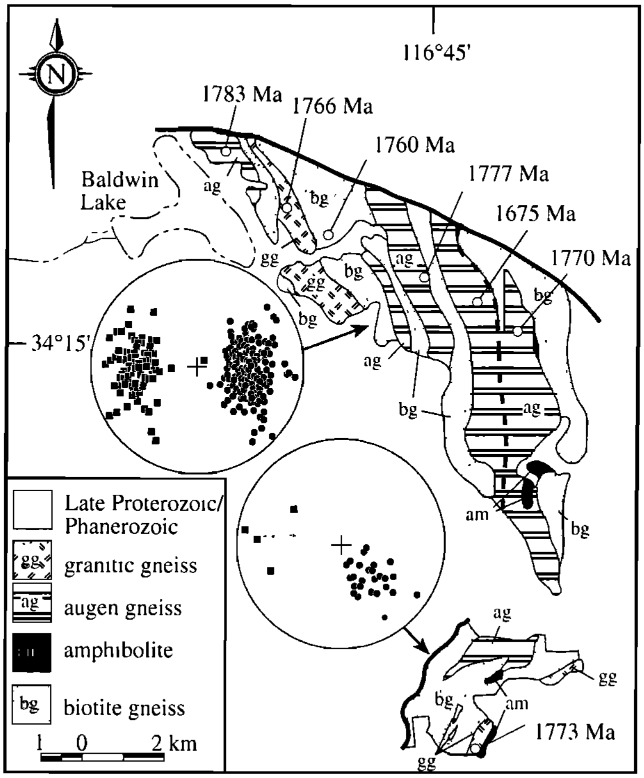

**Figure 3.** Geologic map of Proterozoic rocks in the Baldwin Lake area, central San Bernardino Mountains, southern California. U-Pb zircon sample localities are shown with protolith crystallization or depositional age indicated. Inset stereonets show penetrative $D_2$ deformation fabrics $s_2$ (circles) and $l_2$ (squares) by subarea.

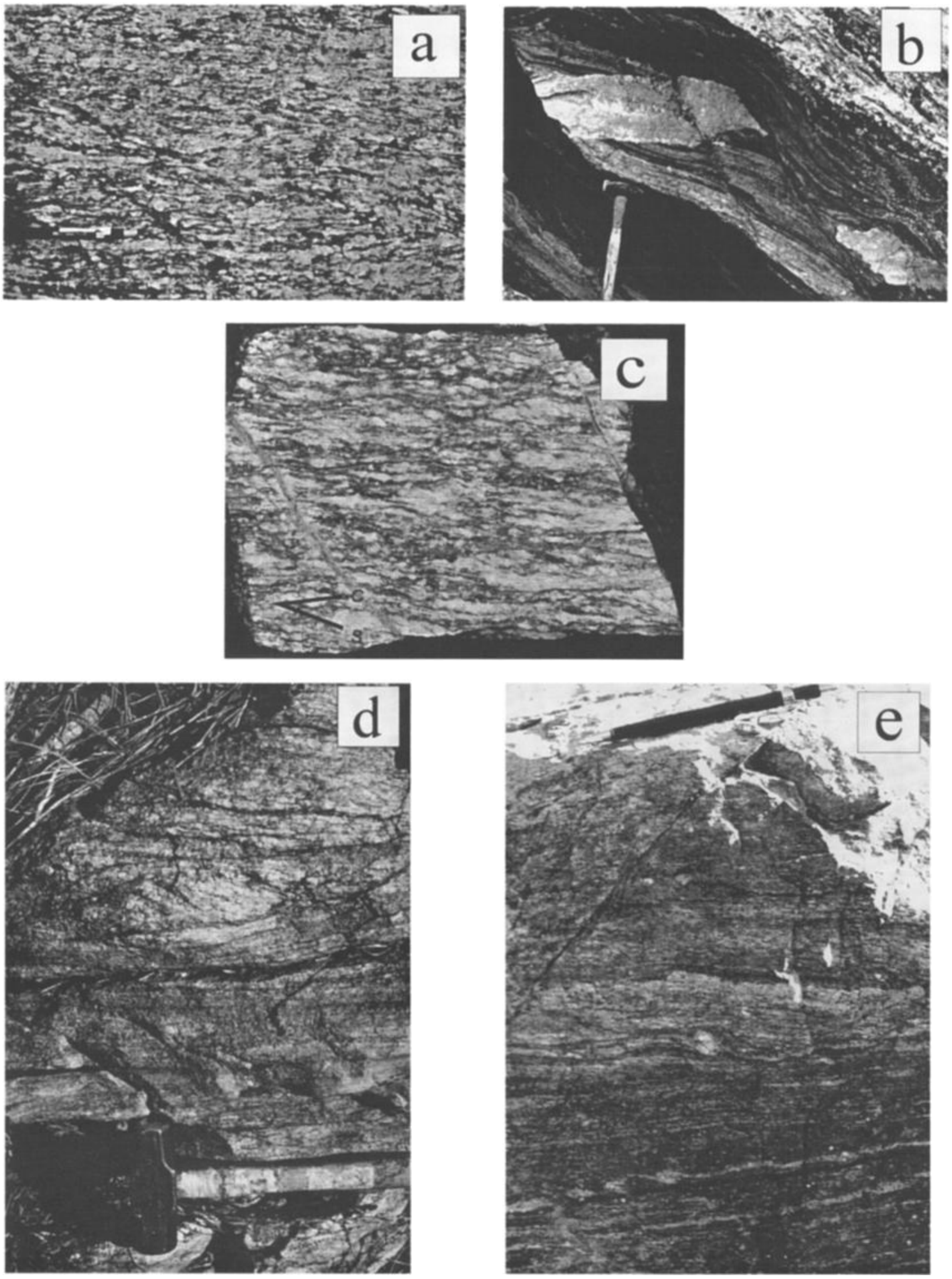

**Figure 4.** Megascopic west vergent fabrics associated with progressive, penetrative $D_2$ deformation in the Baldwin Lake area. (a) Normal-sense shear band cutting foliation in 1770 Ma augen gneiss of Broom Flat (view south). (b) Normal-sense shear zone cutting gneissic foliation in 1675 Ma augen gneiss of Arrastre Creek and synkinematic pegmatite dike (view south). (c) Composite planar fabric in polished slab of 1776 Ma protomylonitic, granitic gneiss of Baldwin Lake (view north). (d) Augen of relatively less deformed quartzofeldspathic gneiss in biotite muscovite gneiss of Baldwin Lake (view north). (e) Mylonitic-ultramylonitic, 1770 Ma augen gneiss of Broom Flat with δ alkali feldspar porphyroclasts (view north).

illustrates relatively homogeneous lithologic units mapped at 1:24,000 scale; geochronologic data described below indicate that these map units include compositionally and texturally similar units with a range of ages. Augen and granitic gneisses are volumetrically dominant in the vicinity of Baldwin Lake. These gneisses include the texturally distinctive augen gneiss of Baldwin Lake, with porphyroclastic alkali feldspar aggregates up to 7 cm in long dimension. The augen gneiss of Arrastre Creek is relatively finer-grained, with porphyroclastic alkali feldspar aggregates up to 3 cm in long dimension. Granitic gneisses are more felsic and have a relict seriate to weakly porphyritic texture with alkali feldspar aggregates up to 1 cm in long dimension. Augen and granitic gneisses are locally intrusive into the biotite muscovite quartzofeldspathic gneiss and schist. Variably deformed pegmatite dikes cut all rock units.

These Proterozoic gneisses comprise a structurally coherent, south trending outcrop belt of middle amphibolite facies L<S tectonites. The predominant fabric is west dipping $s_2$ gneissic compositional banding and schistosity defined by parallelism of micas in all rock types. This fabric is associated with a west plunging $l_2$ feldspar-quartz aggregate rodding and mica streak lineation on foliation surfaces. Tight to isoclinal $f_2$ folds commonly have hinge lines subparallel to this lineation. Outcrop-scale fabric asymmetries in augen, granitic, and quartzofeldspathic gneisses indicate that $s_2$ and $l_2$ formed during a penetrative, progressive episode of west vergent shear ($D_2$). Discrete shear bands and shear zones transect $s_2$, consistently indicating normal-sense simple shear in gneisses and protomylonitic rocks (Figures 4a-4c). In areas of highest strain, mylonitic and ultramylonitic rocks contain augen of feldspar and relatively competent rock fragments surrounded by micaceous matrices that also record west vergent shear (Figures 4d and 4e). Open to tight, mesoscopic folds of gneissic banding are commonly asymmetric and overturned to the west, suggesting they are part of the progressive $D_2$ event. We infer that this event occurred under amphibolite facies conditions at moderate pressure, based on the common occurrence of migmatitic biotite + muscovite quartzofeldspathic gneisses, the rare occurrence of muscovite + fibrolitic sillimanite, and the occurrence of pegmatite dikes that both cut and are cut by west vergent shear zones (Figure 4b).

D2 strain is pervasive and generally precludes deciphering the relative ages of individual rock units in the Baldwin gneiss. However, in areas of low bulk $D_2$ strain an earlier deformation ($D_1$) is recorded by $s_1$ planar fabric in the biotite muscovite quartzofeldspathic gneiss. This $s_1$ fabric is not mineralogically distinct from $s_2$ and therefore is only rarely recognized where it is preserved in xenoliths within weakly strained orthogneisses or is intruded by augen or granitic gneiss with weakly developed $s_2$. Such localities indicate that some augen and granitic gneisses are younger than parts of the biotite muscovite quartzofeldspathic gneiss, although U-Pb zircon data indicate that texturally similar gneisses of a range of ages were interleaved by $D_2$ deformation.

At several locations, gneisses with $D_2$ fabrics are unconformably overlain by upright, latest Proterozoic to Mississippian quartzite, phyllite and marble of the Cordilleran miogeocline, metamorphosed at greenschist facies [see also *Stewart and Poole,* 1975; *Cameron,* 1981]. We conclude from this overlap relationship, and the higher grade of metamorphism of rocks with $D_2$ fabrics that $D_1$ and $D_2$ are latest Proterozoic or older, and we describe below U-Pb zircon results that further constrain the timing of rock formation and deformation in this region.

## 3. U-Pb Geochronologic Results

Pervasive $D_2$ strain does not permit consistent deciphering of cross cutting relationships among rock units in the Baldwin Lake area. Therefore sampling for the U-Pb zircon geochronologic study reported here was designed to date typical rock types within the lithologic units mapped in Figure 3.

### 3.1. Augen Gneiss of Baldwin Lake

Zircons in sample 93JW-232 of the augen gneiss of Baldwin Lake are subhedral grains ranging from equant to prismatic 3:1. The zircons are dark in scanning electron microscopy – cathodoluminescence (SEM-CL) images, exhibiting faint patchy and/or euhedral oscillatory zoning (Figure 5a). Approximately 10% of imaged grains contain a CL-dark, anhedral core, too small to analyze separately with the ion microprobe.

Four conventional zircon fractions in sample 93JW-232 of the augen gneiss of Baldwin Lake yielded discordant U/Pb ages of ~1500-1650 Ma (Table 1). However, poorly constrained upper and lower intercepts and limited data spread preclude geochronologic interpretation. Nine ion microprobe spot analyses from zircon cores are concordant to slightly discordant, yielding an upper intercept age of 1783 +/- 12 Ma that we interpret as the crystallization age of the protolith plutonic rock (Figure 6a; all single grain and intercept ages are reported at the 95% confidence level). Although we avoided regions within zircon grains showing potential for significant Pb loss, the imprecise lower intercept age of 528 +/- 119 Ma may indicate Late Proterozoic to Paleozoic Pb loss associated with development of the unconformity beneath overlying Cordilleran miogeoclinal sediments.

### 3.2. Granitic Gneiss of Baldwin Lake

Zircons in sample 97JW-316 of the granitic gneiss of Baldwin Lake are euhedral to subhedral grains ranging from equant to prismatic 3:1. Most grains have relatively U-poor cores which exhibit either oscillatory zoning (Figure 5b) or are broken and partially resorbed (Figure 5c). All grains are surrounded by CL-dark, faintly oscillatory zoned, U-rich rims.

Seventeen spot analyses of grain interiors ranged from concordant and slightly reversely discordant to extremely normally discordant and lie on a discordia array with an upper intercept age of 1766 +/- 12 Ma and a lower intercept age of ~400 Ma (Figure 6b). We interpret the upper intercept to indicate the crystallization age of the granite protolith and the lower intercept to indicate Paleozoic and possibly younger Pb loss. Two cores (grains 2 and 15) that are not texturally distinctive yielded significantly older $^{207}Pb/^{206}Pb$ ages of 1885 Ma, which we interpret to be xenocrystic zircons. Two analyses of the dark rims (grains 4 and 18) are U-rich, have high U/Th (average is 12), and are extremely discordant. On the basis of compositional characteristics, we interpret these

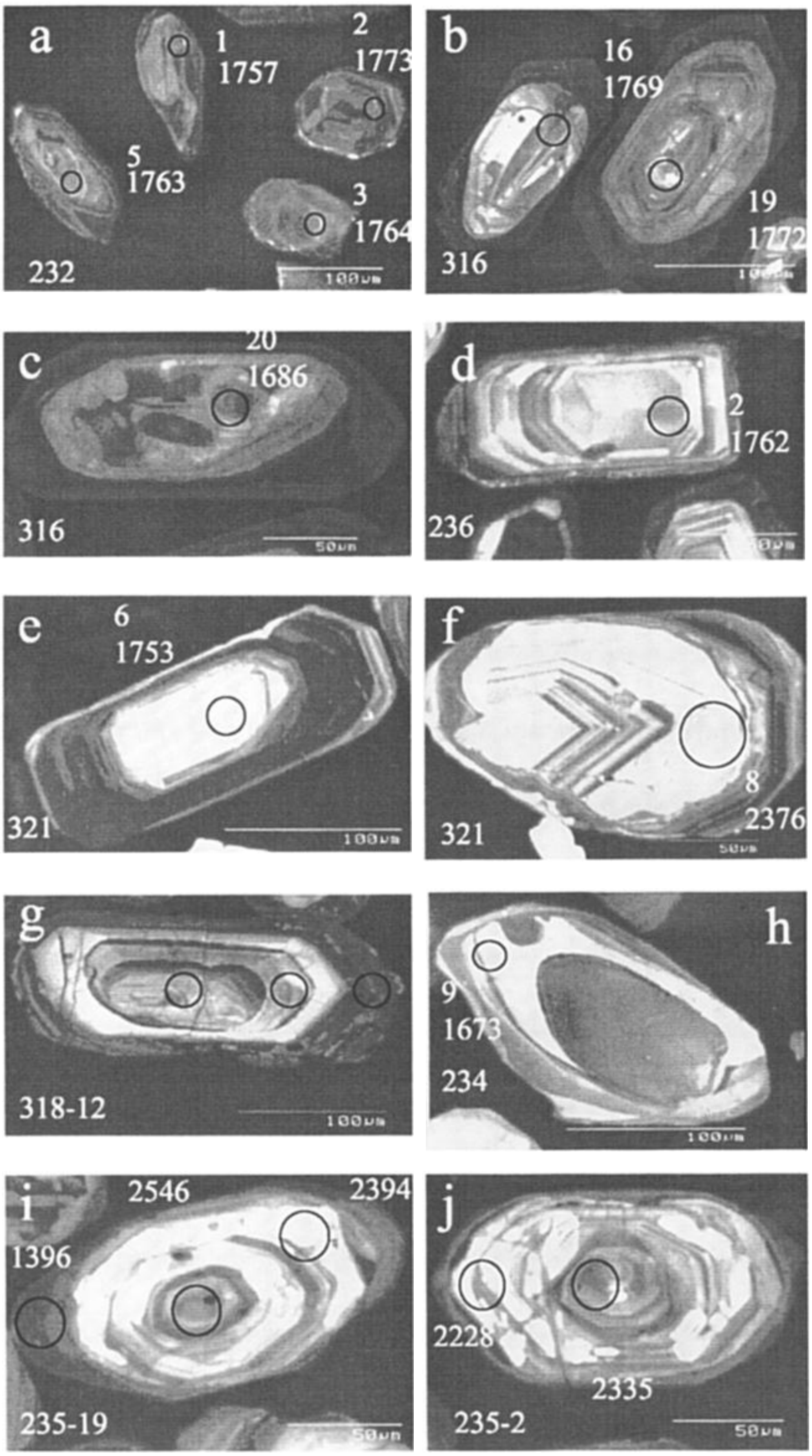

**Figure 5.** Scanning electron microscope - cathodoluminescence photomicrographs of analyzed zircons. Circles show positions of ion microprobe analytical spots that are not always visible on photomicrographs. Note in particular the common occurrence of dark (high U/Th) rims over patchy or oscillatory-zoned cores in all samples except 93-234 (Figure 5h).

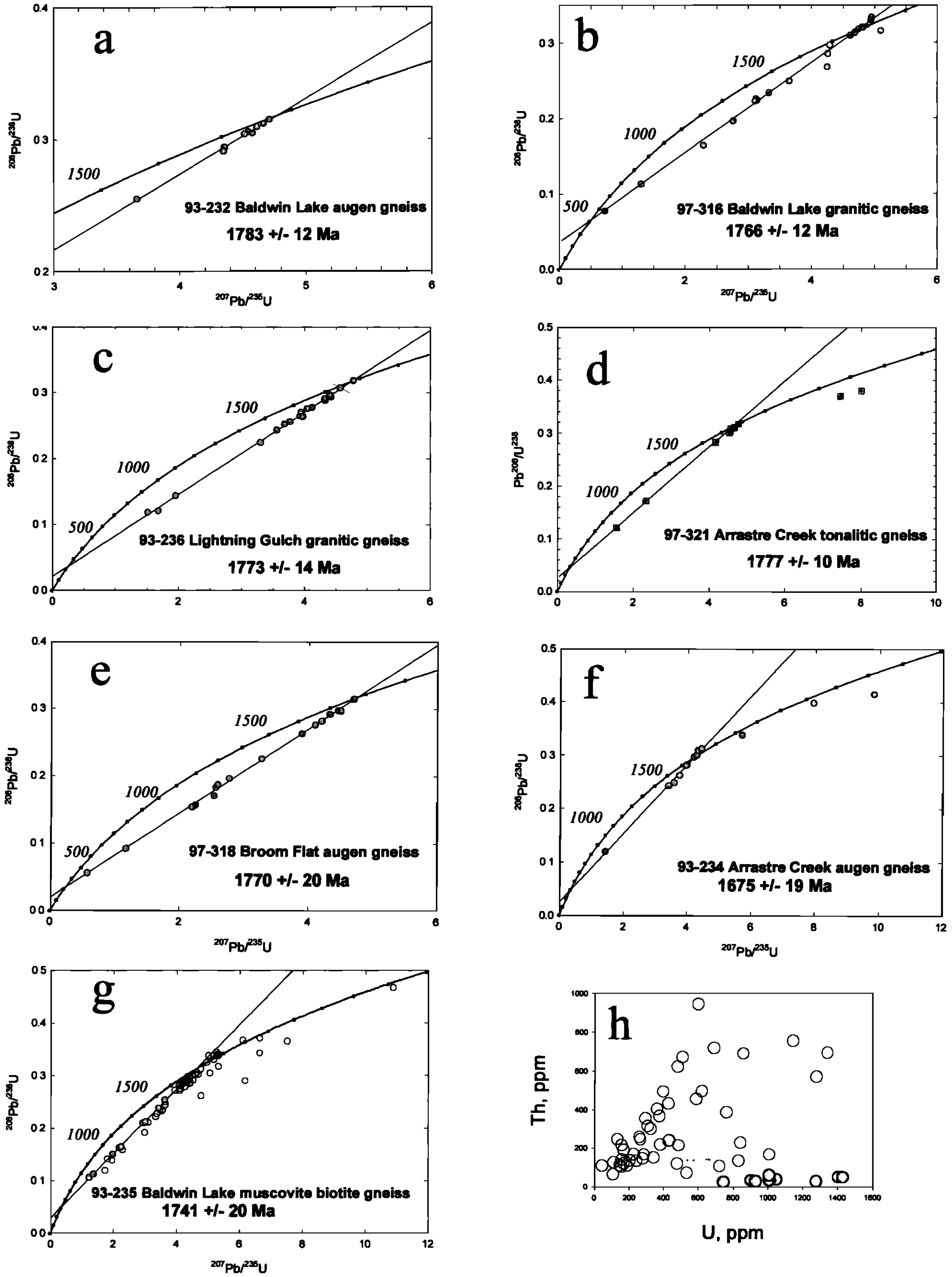

**Figure 6.** U-Pb zircon concordia diagrams for Baldwin gneisses. (a-f) Concordia diagrams for orthogneisses. Concordia upper intercept ages are interpreted as age of crystallization of orthogneiss protolith. Calculated ages are quoted at the 95% confidence level and exclude inherited grains (see text for discussion). (g) Concordia diagram for paragneiss. Concordia upper intercept age is interpreted as time of growth of high U/Th rims (filled circles). Calculated age is quoted at the 95% confidence level and excludes detrital grains (open circles). (h) Uranium and thorium concentrations in zircons from paragneiss, with symbols as in Figure 6g.

**Table 1.** U-Pb Geochronologic Data for Baldwin Gneiss

| Spot[a] | U, ppm[b] | Th, ppm | $^{206}Pb^*/^{238}U$ | $^{207}Pb^*/^{235}U$ | $^{207}Pb^*/^{206}Pb^*$, Ma |
|---|---|---|---|---|---|
| *93JW-232: Augen Gneiss of Baldwin Lake (34°16.95', 116°47.73', sw¼se¼, section 5, T2NR1E)* | | | | | |
| nm-80 | 202.7 | - | 0.25998 | 3.80890 | 1736 |
| nm80-100 | 195.3 | - | 0.26405 | 3.89570 | 1749 |
| nm100-130 | 186.3 | - | 0.27144 | 4.03600 | 1763 |
| nm+130 | 175.2 | - | 0.27255 | 4.08723 | 1779 |
| S1 | 465 | 101 | 0.29397 | 4.3568 | 1757 |
| S2 | 472 | 135 | 0.29104 | 4.3500 | 1773 |
| S3 | 337 | 55 | 0.30564 | 4.5463 | 1764 |
| S4 | 346 | 61 | 0.31496 | 4.7120 | 1774 |
| S5 | 251 | 85 | 0.30399 | 4.5182 | 1763 |
| S6 | 483 | 154 | 0.30469 | 4.5801 | 1783 |
| S7 | 511 | 147 | 0.30933 | 4.6154 | 1770 |
| S8 | 605 | 104 | 0.25492 | 3.6629 | 1700 |
| *93JW-234: Augen Gneiss of Arrastre Creek (34°15.31', 116°44.64', ne¼sw¼, section 14, T2NR2E)* | | | | | |
| m-80 | 315.7 | - | 0.15677 | 2.1074 | 1577 |
| m80-100 | 284.1 | - | 0.16749 | 2.2922 | 1610 |
| nm-80 | 255.2 | - | 0.18094 | 2.4749 | 1609 |
| S3 | - | - | 0.4153 | 9.8286 | 2574 |
| S5 | - | - | 0.3391 | 5.7052 | 1986 |
| S8 | - | - | 0.3991 | 7.9526 | 2282 |
| 5/1 tip | 559 | 170 | 0.28374 | 4.0056 | 1668 |
| 4/1 tip | 453 | 208 | 0.30004 | 4.3062 | 1698 |
| 3/1 end | 139 | 342 | 0.30521 | 4.3195 | 1672 |
| 2/1 | 166 | 318 | 0.3102 | 4.3719 | 1665 |
| 1/1 tip | 396 | 92 | 0.24814 | 3.5603 | 1698 |
| 7/1 | 124 | 263 | 0.28279 | 3.9519 | 1649 |
| 8/1 | 73 | 102 | 0.30943 | 4.3704 | 1669 |
| 9/1 tip | 523 | 107 | 0.24223 | 3.4295 | 1673 |
| 10/1 end | 1093 | 50 | 0.11936 | 1.4226 | 1348 |
| 11/1 | 106 | 209 | 0.30385 | 4.3171 | 1680 |
| 12/1 | 546 | 97 | 0.25973 | 3.7213 | 1695 |
| *93JW-235: Biotite Muscovite Gneiss of Baldwin Lake (34°16.25', 116°46.61', sw¼nw¼, section 9, T2NR1E)* | | | | | |
| nm63-80 | 329.3 | - | 0.17297 | 2.5049 | 1715 |
| nm80-100 | 312.8 | - | 0.17740 | 2.5909 | 1730 |
| nm100-130 | 299.2 | - | 0.17967 | 2.6382 | 1740 |
| nm+130 | 281.3 | - | 0.18270 | 2.6934 | 1748 |
| 1/1 | 312 | 97 | 0.28116 | 4.1526 | 1751 |
| 1/2 | 464 | 76 | 0.2728 | 3.9639 | 1721 |
| 2/1 | 698 | 451 | 0.36581 | 7.5182 | 2335 |
| 2/2 | 400 | 60 | 0.34385 | 6.6416 | 2228 |
| 3/1 | 1008 | 169 | 0.23545 | 3.4801 | 1752 |
| 3/2 | 207 | 138 | 0.29169 | 4.5355 | 1845 |
| 5/1 | 109 | 67 | 0.34099 | 5.3654 | 1866 |
| 5/2 | 281 | 148 | 0.22281 | 3.3526 | 1785 |
| 6/1 | 599 | 948 | 0.1589 | 2.3804 | 1721 |
| 7/1 | 190 | 112 | 0.30283 | 4.6946 | 1839 |
| 8/1 | 113 | 129 | 0.34084 | 5.3243 | 1853 |
| 9/1 | 148 | 114 | 0.33844 | 5.0273 | 1761 |
| 10/1 | 345 | 153 | 0.3383 | 5.2834 | 1852 |
| 11/1 | 591 | 457 | 0.27893 | 4.2723 | 1817 |
| 12/1 | 484 | 624 | 0.2753 | 4.1398 | 1784 |
| 13/1 | 436 | 243 | 0.45029 | 9.57 | 2392 |
| 13/2 | 433 | 241 | 0.36768 | 6.1091 | 1964 |
| 14/1 | 430 | 433 | 0.28884 | 4.2857 | 1759 |
| 15/1 | 623 | 498 | 0.37186 | 6.6426 | 2092 |
| 16/1 | 228 | 170 | 0.3387 | 5.3294 | 1866 |
| 17/1 | 297 | 357 | 0.32543 | 4.9709 | 1812 |
| 18/1 | 134 | 249 | 0.34495 | 5.2662 | 1811 |
| 19/1 | 690 | 720 | 0.29095 | 6.1888 | 2394 |
| 19/2 | 377 | 368 | 0.46772 | 10.887 | 2546 |
| 20/1 | 489 | 216 | 0.23408 | 3.555 | 1802 |
| 22/1 | 160 | 144 | 0.29488 | 4.4187 | 1777 |
| 23/1 | 269 | 248 | 0.31313 | 4.7782 | 1810 |
| 24/1 | 171 | 193 | 0.28804 | 4.3382 | 1787 |
| 25/1 | 1280 | 571 | 0.14193 | 1.8257 | 1494 |
| 26/1 | 510 | 672 | 0.31835 | 5.3382 | 1980 |
| 27/1 | 313 | 317 | 0.3028 | 4.6088 | 1806 |
| 28/1 | 45 | 111 | 0.28242 | 4.1007 | 1720 |

**Table 1.** (continued)

| Spot[a] | U, ppm[b] | Th, ppm | $^{206}Pb^*/^{238}U$ | $^{207}Pb^*/^{235}U$ | $^{207}Pb^*/^{206}Pb^*$, Ma |
|---|---|---|---|---|---|
| *93JW-235: Biotite Muscovite Gneiss of Baldwin Lake (34°16.25', 116°46.61', sw¼nw¼, section 9, T2NR1E)* (continued) | | | | | |
| 29/1 | 159 | 217 | 0.29102 | 4.3124 | 1757 |
| 30/1 | 329 | 302 | 0.23553 | 3.5773 | 1802 |
| 31/1 | 263 | 260 | 0.29172 | 4.383 | 1782 |
| 32/1 | 365 | 406 | 0.30558 | 5.0731 | 1962 |
| 33/1 | 762 | 389 | 0.26226 | 4.7944 | 2132 |
| 34/1 | 400 | 496 | 0.28639 | 4.2274 | 1750 |
| 35/1 | 383 | 220 | 0.27218 | 4.1099 | 1791 |
| 36/1 | 859 | 691 | 0.19206 | 3.005 | 1856 |
| 38/1 | 1343 | 694 | 0.12003 | 1.7471 | 1724 |
| 37/1 | 171 | 124 | 0.28565 | 4.4227 | 1837 |
| 39/1 | 246 | 137 | 0.33123 | 5.1876 | 1858 |
| 1/3 | 482 | 122 | 0.28463 | 4.1775 | 1739 |
| 45/2 | 156 | 105 | 0.30638 | 4.6565 | 1803 |
| 46/1 | 288 | 169 | 0.21146 | 3.1193 | 1749 |
| 48/1 | 536 | 75 | 0.2873 | 4.4416 | 1834 |
| 40/1 | 1144 | 756 | 0.13886 | 1.9745 | 1681 |
| 43/1 | 831 | 137 | 0.22854 | 3.3957 | 1762 |
| 44/1 | 843 | 229 | 0.25057 | 3.6482 | 1725 |
| 4/2 | 723 | 109 | 0.24447 | 3.6401 | 1766 |
| 4/1 rim | 1051 | 39 | 0.1558 | 2.0946 | 1577 |
| 41/1 rim | 904 | 36 | 0.23911 | 3.4337 | 1699 |
| 42/1 rim | 932 | 30 | 0.21036 | 2.9549 | 1659 |
| 8/2 rim | 1010 | 37 | 0.25437 | 3.6445 | 1695 |
| 45/1 rim | 747 | 27 | 0.21232 | 3.0257 | 1685 |
| 15/2 rim | 1279 | 29 | 0.1509 | 1.9934 | 1544 |
| 47/1 rim | 1408 | 52 | 0.10644 | 1.243 | 1309 |
| 19/3 rim | 1431 | 51 | 0.11307 | 1.3818 | 1396 |
| 22/2 rim | 1010 | 62 | 0.16495 | 2.2543 | 1608 |
| *93JW-236: Granitic Gneiss of Lightning Gulch (34°10.45', 116°45.14', nw¼nw¼, section 14, T1NR2E)* | | | | | |
| 1/1 | 588 | 296 | 0.29412 | 4.431 | 1787 |
| 2/1 | 414 | 284 | 0.30806 | 4.5782 | 1762 |
| 3/1 | 641 | 174 | 0.27815 | 4.1293 | 1760 |
| 4/2 | 558 | 334 | 0.25678 | 3.7773 | 1759 |
| 5/1 | 527 | 323 | 0.26566 | 3.9378 | 1744 |
| 6/1 | 855 | 362 | 0.25321 | 3.691 | 1727 |
| 7/1 | 449 | 128 | 0.27652 | 4.0514 | 1736 |
| 8/1 | 522 | 193 | 0.24395 | 3.5647 | 1731 |
| 9/1 | 417 | 176 | 0.28881 | 4.3321 | 1779 |
| 9/2 | 484 | 226 | 0.27126 | 3.947 | 1724 |
| 10/1 | 593 | 386 | 0.3189 | 4.7877 | 1781 |
| 11/1 | 986 | 185 | 0.12121 | 1.6885 | 1643 |
| 12/1 | 469 | 253 | 0.29147 | 4.3318 | 1762 |
| 13/1 | 439 | 180 | 0.26428 | 3.9828 | 1788 |
| 14/1 | 1026 | 160 | 0.14413 | 1.9598 | 1598 |
| 15/1 | 767 | 530 | 0.22523 | 3.3088 | 1741 |
| 16/1 rim | 1476 | 927 | 0.11909 | 1.5173 | 1475 |
| *97JW-316: Granitic Gneiss of Baldwin Lake (34°16.41', 116°47.25', sw¼nw¼, section 9, T2NR1E)* | | | | | |
| 1/1 | 428 | 241 | 0.33387 | 4.9553 | 1760 |
| 2/1 | 525 | 304 | 0.26808 | 4.2591 | 1883 |
| 3/1 | 345 | 115 | 0.30977 | 4.6215 | 1769 |
| 4/1 rim | 817 | 94 | 0.19648 | 2.7642 | 1661 |
| 5/1 | 1432 | 853 | 0.11353 | 1.3085 | 1283 |
| 6/1 | 574 | 214 | 0.297 | 4.2981 | 1714 |
| 7/1 | 365 | 92 | 0.32026 | 4.8143 | 1783 |
| 8/1 | 474 | 226 | 0.31351 | 4.6877 | 1773 |
| 9/1 | 332 | 74 | 0.24987 | 3.6553 | 1733 |
| 10/1 | 428 | 109 | 0.32991 | 4.9472 | 1779 |
| 12/1 | 821 | 367 | 0.16458 | 2.2991 | 1648 |
| 13/1 | 776 | 270 | 0.22441 | 3.1479 | 1656 |
| 14/1 | 313 | 207 | 0.32058 | 4.8107 | 1780 |
| 15/1 | 49 | 24 | 0.31595 | 5.1004 | 1912 |
| 16/1 | 414 | 229 | 0.31783 | 4.7412 | 1769 |
| 17/1 | 832 | 104 | 0.22583 | 3.1302 | 1634 |
| 18/1 rim | 1984 | 134 | 0.07805 | 0.7277 | 857 |
| 19/1 | 359 | 87 | 0.28563 | 4.2668 | 1772 |
| 20/1 | 703 | 116 | 0.23406 | 3.3363 | 1686 |

**Table 1.** (continued)

| Spot[a] | U, ppm[b] | Th, ppm | $^{206}Pb^*/^{238}U$ | $^{207}Pb^*/^{235}U$ | $^{207}Pb^*/^{206}Pb^*$, Ma |
|---|---|---|---|---|---|
| *97JW-318: Augen Gneiss of Broom Flat (34°15.34', 116°44.04', nw¼sw¼, section 13, T2NR2E)* | | | | | |
| 1/1 | 581 | 147 | 0.15731 | 2.2487 | 1691 |
| 2/1 | 718 | 263 | 0.15445 | 2.1965 | 1681 |
| 3/1 | 283 | 117 | 0.29258 | 4.3314 | 1755 |
| 4/1 | 319 | 70 | 0.22641 | 3.2762 | 1713 |
| 5/1 | 433 | 232 | 0.27665 | 4.1042 | 1759 |
| 6/1 | 166 | 101 | 0.29814 | 4.4642 | 1776 |
| 7/1 | 272 | 81 | 0.29741 | 4.5085 | 1798 |
| 8/1 | 338 | 152 | 0.31503 | 4.7041 | 1771 |
| 9/1 | 433 | 123 | 0.19748 | 2.7745 | 1659 |
| 11/1 | 173 | 64 | 0.28237 | 4.2045 | 1766 |
| 12/1 | 528 | 167 | 0.18343 | 2.5656 | 1651 |
| 12/2 | 490 | 174 | 0.26411 | 3.8983 | 1750 |
| 12/3 rim | 1840 | 211 | 0.0564 | 0.5817 | 1063 |
| 13/1 | 673 | 96 | 0.18795 | 2.5978 | 1629 |
| 14/1 | 490 | 47 | 0.17104 | 2.5417 | 1762 |
| *97JW-321: Tonalitic Gneiss of Arrastre Creek (34°15.65', 116°44.96', ne¼nw¼, section 14, T2NR2E)* | | | | | |
| 1/1 | 236 | 167 | 0.30358 | 4.55995 | 1782 |
| 2/1 | 238 | 166 | 0.2829 | 4.1705 | 1748 |
| 3/1 | 251 | 67 | 0.17179 | 2.3369 | 1599 |
| 4/1 | 567 | 121 | 0.3699 | 7.457 | 2302 |
| 5/1 | 205 | 146 | 0.31714 | 4.7673 | 1783 |
| 6/1 | 170 | 177 | 0.30858 | 4.562 | 1753 |
| 7/1 | 155 | 72 | 0.31102 | 4.6641 | 1779 |
| 8/1 | 234 | 101 | 0.38021 | 8.0043 | 2376 |
| 9/1 | 219 | 104 | 0.3094 | 4.6283 | 1774 |
| 9/2 rim | 1231 | 99 | 0.12143 | 1.553 | 1483 |
| 11/1 | 219 | 190 | 0.30082 | 4.5273 | 1785 |

a Abbreviations for conventional zircon fractions are m, magnetic; nm, non-magnetic; for SHRIMP ion microprobe spots, all analyses are from interiors of grains, except as noted.

b Uranium and lead concentrations and isotopic compositions in bulk zircon fractions were analyzed on a Finnigan MAT 262 thermal ionization mass spectrometer at the U.S. Geological Survey in Menlo Park. Analytical techniques were reported by *Barth et al.* [1997]. Uranium and thorium concentrations and isotopic compositions of individual zircon grains were analyzed using the SHRIMP I and II ion microprobes at the Australian National University. Replicate analyses of standard zircon AS-3 (1099 Ma) were used to calibrate U and Th concentrations and Pb isotopic compositions. SHRIMP measurement and data reduction procedures followed *Williams* [1997].

rims as originating during ca. 1741 Ma metamorphism (see discussion below).

### 3.3. Granitic Gneiss of Lightning Gulch

Zircons in sample 93JW-236 of the granitic gneiss of Lightning Gulch are euhedral to subhedral, equant to prismatic 5:1. Most grains have oscillatory-zoned, low-U cores (Figure 5d). Approximately 30% of the grains examined also contain a dark structureless core within this oscillatory-zoned interior. All analyzed grains exhibit thin, CL-dark rims that could not be analyzed separately but appear similar to those observed in the Baldwin Lake granitic gneiss.

Seventeen spot analyses of zircon interiors yielded discordant U-Pb ages. The discordia array yields an upper intercept age of 1773 +/- 14 Ma (Figure 6c) consistent with the most concordant age of 1781 Ma age for grain 10. The lower intercept of ~250 Ma indicates younger Pb loss.

### 3.4. Tonalitic Gneiss of Arrastre Creek

Zircons in sample 97JW-321 of the tonalitic gneiss of Arrastre Creek are euhedral to subhedral grains ranging from equant to prismatic 4:1. Relatively U-poor cores with oscillatory zoning are present in ~50% of grains (Figure 5e), with the balance of grains having darker cores. All grains are surrounded by faintly zoned, CL-dark rims. Some grains also retain a very thin, CL-bright outermost partial rim, too thin to be analyzed by ion microprobe.

Ten grain interiors and a single CL-dark rim were analyzed; seven cores are concordant to slightly discordant and yield an age of 1777 +/- 10 Ma (Figure 6d), which we interpret to be the crystallization age of the tonalite protolith. The core of grain 3 and the rim of grain 9 are very discordant as a result of younger Pb loss, though the timing of Pb loss is poorly constrained on the basis of these two data points alone. Grains 4 and 8 are resorbed (Figure 5f) and yielded $^{207}Pb/^{206}Pb$ minimum ages of 2300-2400 Ma. We interpret these data to indicate that these grains were inherited from the tonalite source region.

### 3.5. Augen Gneiss of Broom Flat

Zircons in sample 97JW-318 of the augen gneiss of Broom Flat are euhedral to subhedral, equant to prismatic 3:1. Most grains exhibit oscillatory-zoned, CL-bright interiors surrounded by faintly zoned, CL-dark rims (Figure 5g). About 30% of the grains also have partial, very thin CL-bright rims that could not be isolated with the ion microprobe.

Thirteen spot analyses of grain interiors yielded a discordia array with an upper intercept 1770 +/- 20 Ma (Figure 6e), consistent with the most concordant age of 1771 Ma for grain 8. The lower intercept of ~200 Ma indicates Paleozoic and younger Pb loss. Analysis 12/3 is from the CL-dark rim of grain 12 (Figure 5g) and is typical of the dark rims present in this sample. Its very high U content and U/Th = 9, compared to an average core U/Th = 3, indicate that rims are metamorphic, similar to the CL-dark, high-U/Th rims in granitic gneisses.

### 3.6. Augen Gneiss of Arrastre Creek

The augen gneiss of Arrastre Creek (93JW-234) contains zircons that are euhedral to subhedral, equant to prismatic 3:1. All zircon grains exhibit CL-bright oscillatory zoning (Figure 5h), occasionally containing a dark, featureless core. These grains lack the prominent CL-dark rims observed in previously described samples.

Nineteen zircon interiors and rims were analyzed, 14 of which are concordant to slightly discordant with an upper intercept age of 1675 +/- 19 Ma (Figure 6f), which we interpret as the igneous crystallization age of the orthogneiss. Three grains (S3, S5, and S8) yielded $^{207}Pb/^{206}Pb$ ages of 1950-2600 Ma and are interpreted to have been inherited from the source region of the orthogneiss protolith.

### 3.7. Biotite Muscovite Gneiss of Baldwin Lake

Sample 93JW-235 was collected from the biotite muscovite quartzofeldspathic gneiss of Baldwin Lake, which is interpreted to be a paragneiss based on the abundance of quartz and muscovite. Zircons in this sample are mostly subhedral, equant to prismatic 2:1 to rarely 3:1. Interiors of grains are of two types: some are oscillatory zoned and CL-bright (Figures 5i and 5j), and others are darker, generally featureless grains which are fractured and partially resorbed, with relatively brighter overgrowths. All grains exhibit faintly oscillatory-zoned, CL-dark rims.

This sample exhibits much more complex U-Th-Pb systematics than any other sample (Figure 6g), consistent with our interpretation of a metasedimentary origin for this map unit. All grain interiors are relatively U-poor and have low U/Th (average is 1.5). CL-bright, oscillatory- zoned grains yield Archean-early Proterozoic $^{207}Pb/^{206}Pb$ ages ranging from 1970 to 2700 Ma. The darker, featureless grain cores comprise the dominant population, with most $^{207}Pb/^{206}Pb$ ages ranging from 1760 to 1870 Ma. We interpret the age of grain interiors to record detrital grain ages and the lower limit of this range of detrital grain ages as constraining the maximum depositional age for this rock at ~1760 Ma.

The CL-dark rims on both of these two populations of detrital grains comprise a third unique population in terms of the U-Th-Pb system (Figures 6g and 6h). These rims are U-enriched relative to zircon interiors, with high-U/Th (average is 27), and form a distinct discordia array with an upper intercept of 1741 +/- 20 Ma. We interpret these rims to date the first metamorphism of this metasediment and other units containing texturally similar, high U/Th rims, including the granitic gneisses of Baldwin Lake and Lightning Gulch, the tonalitic gneiss of Arrastre Creek, and the augen gneisses of Broom Flat (compare Figures 5c, 5e, 5g, 5i and 5j). This interpretation is consistent with protolith crystallization ages of 1783-1766 Ma for these orthogneiss units and the lack of metamorphic rims in the 1675 Ma augen gneiss of Arrastre Creek.

## 4. Discussion

Proterozoic gneisses in the San Bernardino Mountains are the westernmost exposed part of the Mojave crustal province and provide new insights into both the origin and early evolution of the province and its later tectonic evolution. U-Pb geochronologic data indicate that Baldwin orthogneisses are older than those in the eastern part of the province, which have a maximum age of 1760 Ma and are mostly <1740 Ma [*Wooden and Miller*, 1990]. Furthermore, Baldwin orthogneisses clearly record interaction with preexisting crust, based on the more common occurrence of inherited zircons. In addition to providing insights into the early history of the Mojave province, the Baldwin gneiss, when compared to other, less well studied Proterozoic rocks in the Transverse Ranges, suggests a more protracted tectonic evolution for the western Mojave province. West vergent $D_2$ deformation and amphibolite facies metamorphism affect rocks as young as the 1675 Ma augen gneiss of Arrastre Creek, and are therefore younger than the 1.7 Ga Ivanpah orogeny, the major orogenic event in the eastern part of the province. In the discussion that follows, we summarize these correlations and use them to construct a testable hypothesis for the Early Proterozoic evolution of the Mojave and adjacent provinces.

### 4.1. Origin of the Proterozoic Gneisses in the San Bernardino Mountains

Deposition of greywacke, quartz wacke, and minor quartzite commenced prior to ~1770 Ma, the age of most augen and granitic gneisses which locally intrude the metasediments, yet sedimentation continued to at least ~1750 Ma, the inferred depositional age of paragneiss sample 93JW-235. Sediments were derived from both Archean and Early Proterozoic sources (1970-2700 Ma and 1760-1870); the significant ~1800-1850 Ma detrital component in the biotite muscovite gneiss of Baldwin Lake suggests that an arc terrane of this age lay nearby. Plutonism and continued sedimentation occurred between 1783 and 1766 Ma, forming the protoliths of tonalitic gneiss of Arrastre Creek, augen gneisses of Baldwin Lake and Broom Flat, and granitic gneisses of Baldwin Lake and Lightning Gulch. The alkali contents and lack of iron enrichment in these plutonic rocks indicate a calc-alkalic affinity [*Peacock*, 1931; *Irvine and Baragar*, 1971], and we infer that emplacement was in an arc setting [*Flodin et al.*, 1997]. Most metaplutonic samples analyzed thus far contain Archean and/or Early Proterozoic inherited zircons with minimum ages of 1850-1950 and 2400-2600 Ma, suggesting that this region was underlain by Archean and Early Proterozoic crust or proximal sediments derived from such crust. Sediment containing these older components continued to be delivered to the arc during plutonism. These results suggest that 2.0-2.3 Ga Nd depleted mantle model ages that characterize the Mojave province [*Bennett and DePaolo*, 1987] could result largely from mixing of Late Archean and late Early Proterozoic (partly juvenile) components [*Coleman et al.*, 1999].

The ubiquitous occurrence of CL-dark, high U/Th rims on

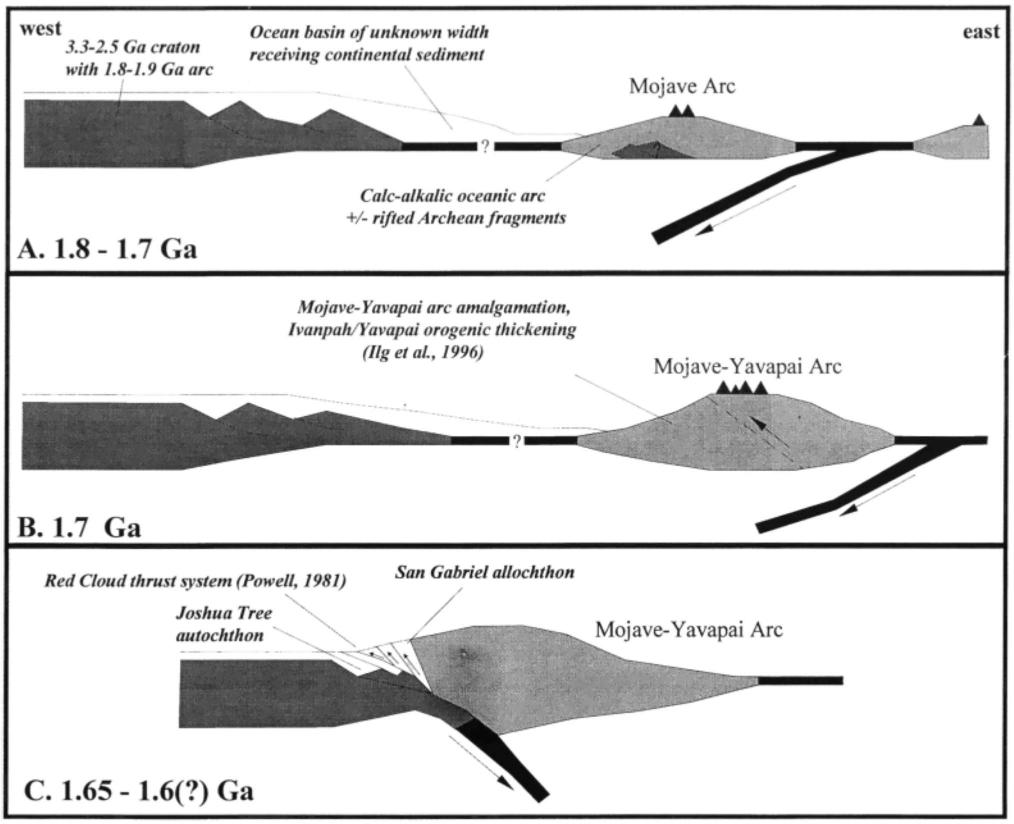

**Figure 7.** Tectonic cartoons illustrating the Early Proterozoic evolution of the southwestern United States. (a) 1.8-1.7 Ga. The Mojave oceanic arc is constructed in proximity to an Archean-Early Proterozoic craton providing quartz-rich sediment and detrital zircons. (b) 1.7 Ga. Yavapai and Mojave arcs amalgamated during high-grade metamorphism (Yavapai/Ivanpah orogeny), principally by northwest directed deformation. Northwest directed subduction continues outboard beneath heated and thickened arc crust until ca. 1.65 Ga (Mazatzal orogeny). (c) West directed thrusting of the composite Mojave/Yavapai arc along the Red Cloud thrust over the shelf and slope of the adjacent craton, now preserved as (para)autochthonous Joshua Tree terrane. Timing of this event is not yet well constrained (1.65-1.4 Ga) but is inferred to be between 1.65 and 1.6 Ga.

zircons from 1783 to 1766 Ma orthogneisses and their probable correlation to dated zircon rims in the biotite muscovite paragneiss suggest that most rocks in the Baldwin Lake area experienced metamorphism and consequent development of zircon overgrowths at ~1741 Ma. Given the uncertainties associated with these dates and the penetrative nature of younger deformation, we have not yet determined the grade of metamorphism associated with this event nor whether the zircon overgrowths record a distinct tectonothermal event or reflect a thermal peak in an actively evolving and deforming magmatic arc. The presence of younger arc plutons both in the Baldwin Lake area and further east in the Mojave province suggests the latter is the more likely scenario.

Renewed calc-alkalic arc plutonism occurred at 1675 Ma, represented by the augen gneiss of Arrastre Creek. This age provides a maximum age limit on amphibolite facies metamorphism and $D_2$ west vergent deformation. We have not yet successfully dated synkinematic to postkinematic dikes limiting the timing of $D_2$. However, we suggest that $D_2$ is probably older than the 1189 Ma San Gabriel anorthosite complex and 1.38 - 1.45 Ga granites that are widespread in the Mojave province, although neither of these younger units has been identified in the San Bernardino Mountains.

### 4.2. Accretion of Proterozoic Terranes in California

The Proterozoic tectonostratigraphy of the Transverse Ranges provides constraints for development of a tectonic model for the Proterozoic tectonic evolution of the Mojave province of the southwestern North American craton (Figure 7). Calc-alkalic plutonism, volcanism, and associated sedimentation were widespread across the Mojave province from 1780 to 1660 Ma, recording the development of one or more oceanic arc terranes. These arc rocks evolved on oceanic crust [*Coleman et al.*, 1999] in proximity to or atop fragmented Archean-Early Proterozoic crust, as indicated by the common occurrence of Archean and Early Proterozoic detrital and inherited zircons in amphibolite grade rocks of the San Bernardino Mountains and their local preservation in granulite grade Mojave province rocks to the east.

Between ~1750 and 1700 Ma, while intra-arc extension formed the Payson ophiolite and overlying marine strata in the Mazatzal province [*Dann*, 1991], the Mojave and adjoining Yavapai crustal province enjoyed one or more deformation events [*Wooden and Miller*, 1990; *Karlstrom and Bowring*, 1991; *Ilg et al.*, 1996]. Structures indicative of northwest-southeast shortening in the Mojave-Yavapai transition zone suggest the provinces were amalgamated at this time by intra-arc deformation or arc-arc collision [e.g., *Wooden and DeWitt*, 1991; *Karlstrom and Bowring*, 1991] (Figure 7b). Renewed plutonism between 1685 and 1660 Ma in the Mojave province records continued arc evolution [*Wooden and Miller*, 1991]. The occurrence of granitic rocks with both calc-alkalic and within-plate geochemical signatures [*Bender et al.*, 1993; *Flodin et al.*, 1997] suggests these plutons were intruded following substantial orogenic thickening.

We suggest that arc plutonism ended when thickened Mojave province crust was thrust westward over the continental shelf of the adjacent Archean-Early Proterozoic craton, now preserved as Joshua Tree terrane (Figure 7c). This event is recorded in penetrative west vergent deformation in rocks as young as 1675 Ma in the San Bernardino Mountains, which comprise part of the San Gabriel allochthon above the west-vergent Red Cloud thrust of Powell [1993] (Figure 2). The Joshua Tree (para)autochthon contains granitic rocks as young as 1658 Ma (A.P. Barth et al., unpublished data, 1999), unconformably overlain by a shelf-slope sequence of metasediments [Powell, 1981]. We lack solid minimum geochronologic constraints on development of these fabrics or the Red Cloud thrust, but we infer timing for this event (ca. 1650-1600 Ma) closely associated with the end of widespread calc-alkalic plutonism in the Mojave province and significantly prior to the ca. 1450 Ma onset of regional anorogenic plutonism [*Anderson*, 1983].

Accurate Late Proterozoic plate reconstructions for the southwestern United States are highly dependent on the heritage of this underthrust craton edge, and the source for the Archean-Early Proterozoic detrital and xenocrystic zircons found in western Mojave province rocks. Few data are available as yet to directly characterize the Joshua Tree terrane (para)autochthon, but the Archean Wyoming crustal province to the north lacks equivalent granitic basement or a history of <1658 Ma shelf-slope sedimentation. The Wyoming province is also not likely to be the source of the inherited Archean-Early Proterozoic zircons and isotopic signatures found in rocks of the San Gabriel allochthon because of the much more radiogenic Pb isotopic signature and lack of an ca. 1850 Ma orogenic belt in the exposed Wyoming province. Within the context of existing plate reconstructions for the Late Proterozoic (Figure 1), candidates for correlation include Archean basement of the east Antarctic craton juxtaposed with 1733 +/- 8 Ma augen orthogneiss in the Miller Range of the Transantarctic Mountains [*Goodge et al.*, 1991; *Bennett and Fanning*, 1993; *Borg and DePaolo*, 1994] and Early Proterozoic rocks deformed against Archean basement of the south Australian craton during the Kararan and Olarian orogenies at 1670-1600 Ma [*Myers et al.*, 1996].

It is likely that the model presented here will require substantial modification, given the current lack of detailed structural and geochronologic data on Proterozoic rocks of the Transverse Ranges. However, we believe it represents a testable hypothesis for the tectonic evolution of the Mojave province. It predicts that Joshua Tree terrane contains Archean crust, a ca. 1.8-1.9 Ga arc, and overlying sediments with zircon provenance similar to Baldwin paragneisses and that these rocks are a fragment of the craton which lay west of the Mojave province prior to Cordilleran rifting. It further predicts that the Mojave province and Joshua Tree terrane were consolidated by regional, west vergent collisional deformation, associated with the Red Cloud thrust, that occurred between 1.65 and 1.4 Ga. This hypothesis, when tested, will provide important constraints on the tectonic evolution of western Laurentia and palinspastic reconstruction of Rodinia.

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