Crustal growth and tectonic evolution of the Mojave crustal province: Insights from hafnium isotope systematics in zircons

J.L. Wooden[1], A.P. Barth[2], and P.A. Mueller[3]

[1]DEPARTMENT OF GEOLOGICAL AND ENVIRONMENTAL SCIENCES, STANFORD UNIVERSITY, 450 SERRA MALL, STANFORD, CALIFORNIA 94305, USA
[2]DEPARTMENT OF EARTH SCIENCES, INDIANA UNIVERSITY–PURDUE UNIVERSITY, 723 WEST MICHIGAN STREET, INDIANAPOLIS, INDIANA 46234, USA
[3]DEPARTMENT OF GEOLOGICAL SCIENCES, UNIVERSITY OF FLORIDA, GAINESVILLE, FLORIDA 32611, USA

ABSTRACT

Coupled U-Pb ages and Hf isotopic ratios in zircons from Proterozoic basement and three siliciclastic cover sequences in southern California provide important insights into the formation of the southern Mojave crustal province and its incorporation into southwestern Laurentia. Hafnium isotopic ratios measured in >800 zircons, coupled with new and previously reported U-Pb ages, suggest that the crystalline basement of the Mojave crustal province formed from four main components: 1) mantle components ranging from depleted to moderately enriched; 2) metasedimentary framework rocks derived from 2.6 to 2.4 Ga and 2.0 to 1.8 Ga crust; 3) 1.79 to 1.64 Ga intrusive rocks that reflect mixing of mantle-derived melts and crust; and 4) Mesoproterozoic (1.4 to 1.2 Ga) anorthosite and granitic to syenitic intrusive rocks. Initial Hf isotopic ratios of detrital zircons in siliciclastic cover sequences suggest varying degrees of insularity of the Mojave province during assembly of southwestern Laurentia. The Mesoproterozoic Pinto Mountain Group appears entirely derived from Mojave province basement. In contrast, Neoproterozoic quartzites of the Big Bear Group had a distal provenance, either an unexposed, older, western subprovince of the Mojave crustal province lacking ca. 1.7 Ga magmatic rocks or from a distinctive Paleo- and Mesoproterozoic basement province far to the east within Laurentia. Zircons in latest Neoproterozoic to Cambrian quartzites reflect provenance from an integrated transcontinental drainage network delivering sediment to the craton edge and westward into the Cordilleran miogeocline.

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INTRODUCTION

The Mojave crustal province is an important yet enigmatic component of the southern Laurentian craton. In contrast to the adjacent Yavapai and Mazatzal provinces, the Mojave province records Paleoproterozoic (1.79–1.64 Ga) continental crust formation with widespread incorporation of recycled crustal components ranging in age from 3.42 to 1.8 Ga. Intact Archean crust has not been identified in the Mojave province. Recycling of earliest Paleoproterozoic or Archean crust is indirectly evident in bulk-rock Nd isotopes (McCulloch and Wasserburg, 1978; Bennett and DePaolo, 1987; Rämö and Calzia, 1998; Coleman et al., 2002) and the distinctive nature of bulk-rock Pb isotopes (Wooden et al., 1988; Wooden and Miller, 1990; Wooden and DeWitt, 1991). The most proximal Archean crust within Laurentia lies to the northeast in the older and more isotopically evolved Archean Wyoming province. The identity and means of incorporation of older crustal components into the Mojave province, whether from the Wyoming or some other Archean craton, are ambiguous in bulk-rock geochemistry (e.g., Nelson et al., 2011), yet characterization of recycled components is critical for understanding both the processes of recycling during crust formation and the positioning of the province relative to Proterozoic supercontinents such as Nuna and Rodinia (Burrett and Berry, 2000; Sears and Price, 2003; Stewart et al., 2010; Evans and Mitchell, 2011).

To better characterize the origin of the province, and especially the sources and the relative roles of juvenile and recycled crustal components in crust formation, we measured Hf isotopic compositions of zircons analyzed for U-Pb geochronology by conventional means and by ion microprobe (Wooden and Miller, 1990; Wooden et al., 1994; Barth et al., 2000, 2001, 2009; this study). Hf isotopic data from spots within individual zircons of known crystallization age are particularly useful because they avoid the averaging effect of bulk-rock Nd and Pb measurements and Hf isotopic measurements on solutions from either bulk zircon mineral separates or individual whole grains. Zircon subgrain isotopic data are also useful to properly assign metamorphic and/or original crystallization ages, and thereby characterize zircon provenance, as well as identify zircons retained and delivered as siliciclastic sediment to other parts of Laurentia and Rodinia and/or delivered to the Mojave province subsequent to its incorporation into Laurentia. In this report, we describe a database of >800 U-Pb–Lu-Hf isotope pairs: 159 analyses of detrital zircons from basement metasedimentary rocks, 281 analyses of zircons from basement intrusive rocks, 69 analyses of zircons from younger Mesoproterozoic granitic and syenitic intrusions, and 55 analyses of zircons from a Mesoproterozoic AMCG (anorthosite-mangerite-charnockite-granite) suite. These basement zircons are compared to 299 detrital zircons from Proterozoic to Cambrian sedimentary cover sequences to define the origin of the basement in the province and to illustrate the potential of coupled U-Pb–Lu-Hf isotopic analyses for identifying distinctive provenance age and isotopic signatures in detrital zircon suites and their original crystalline host rocks.

PREVIOUS WORK

Exposed Proterozoic basement in southwestern Laurentia is primarily composed of the relatively juvenile, Paleoproterozoic Yavapai and Mazatzal crustal provinces. However, the Mojave crustal province (“Mojavia” of Bennett and DePaolo, 1987) has been recognized as a geochronologically

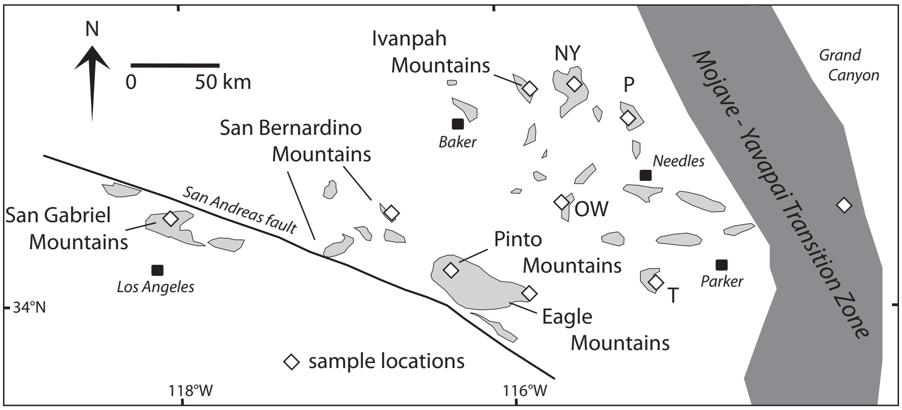

Figure 1. Generalized geologic map of the southern Mojave crustal province, showing regions of outcrop of Proterozoic rocks, and ranges where Paleoproterozoic basement and cover sequences were sampled for this study. Abbreviations: NY—New York Mountains, OW—Old Woman Mountains, P—Piute Range, T—Turtle Mountains.

and geochemically discrete Paleoproterozoic domain that lies between these interior crustal provinces and the Phanerozoic rifted plate margin of Laurentia (Fig. 1). The Mojave province is characterized by crustal rocks with crystallization ages of ca. 1.7 Ga (Wooden and Miller, 1990), and by whole-rock initial $^{143}Nd/^{144}Nd$ ratios that are typically significantly lower than Paleoproterozoic depleted mantle and lower than rocks of equivalent age from the Yavapai and Mazatzal provinces. As a result, whole-rock, Sm-Nd depleted mantle model ages for the Mojave province range from 2.7 to 1.7 Ga, with a mean age of ca. 2.2 Ga (Bennett and DePaolo, 1987; Martin and Walker, 1992; Rämö and Calzia, 1998; Coleman et al., 2002; Fig. 2). The Mojave province is equally distinctive in feldspar and whole-rock Pb isotopic compositions, with whole-rock Pb isotopic ratios indicating crust formation and evolution characterized by high U/Pb and Th/Pb, and subsequent evolution with Th/U significantly higher than the crustal average (Wooden et al., 1988; Wooden and DeWitt, 1991). These whole-rock isotopic data suggest that the Mojave crustal province likely originated by incorporation of Archean crust into an evolving convergent margin environment, or by formation of the province at a convergent margin developed at least in part on Archean lithospheric mantle or younger mantle enriched by fluids derived from subducted Archean sediment.

Mapping and U-Pb geochronology (Young et al., 1989; Miller and Wooden, 1992; Wooden et al., 1994; Barth et al., 2000, 2009; Strickland et al., 2009; Figs. 3 and 4) outline the temporal evolution of the province and set the framework for Hf isotopic analyses. Gabbroic, trondhjemitic, tonalitic, and granitic orthogneisses, with crystallization ages between ca. 1.79 and 1.73, intruded an older lithologic assemblage composed of mostly immature metasedimentary rocks, rare quartzite, and 1.81 Ga amphibolite with initial $^{143}Nd/^{144}Nd$ ratios suggesting derivation from an enriched mantle source. Metasedimentary rocks contain detrital zircons as old as 3.3 Ga, but detrital zircons with ages from 1.9 to 1.8 Ga predominate. These observations suggest initial crust formation in a marginal marine arc environment overlying enriched mantle, providing the framework rocks for 1.79–1.73 Ga intrusions. All rocks older than 1.73 Ga are penetratively deformed and metamorphosed. Individual samples record

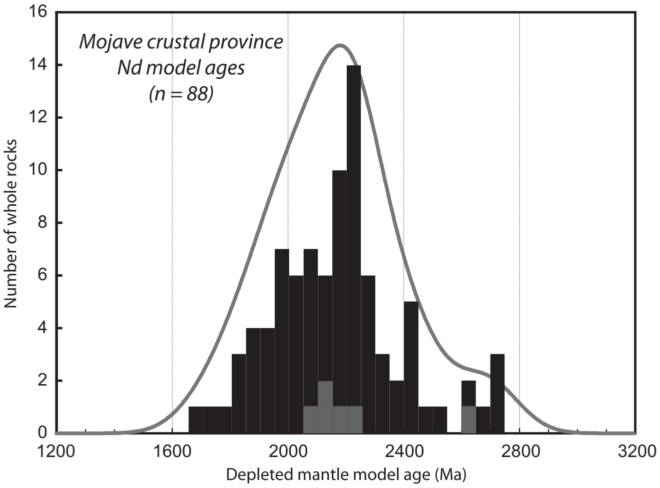

Figure 2. Summary histogram and probability plot of published Nd depleted mantle model ages for whole rocks with crystallization ages between ca. 1.8 and 1.4 Ga from the Mojave crustal province. Model ages range from 1.7 to 2.7 Ga, and mean model age of the province is ca. 2.2 Ga. Lighter symbols highlight whole-rock values for 1.81 Ga amphibolites indicative of the presence of enriched mantle at ca. 1.8 Ga. Data sources: Bennett and DePaolo (1987), Martin and Walker (1992), Rämö and Calzia (1998), Coleman et al. (2002), and D.S. Coleman, 1999, personal commun., depleted mantle model of DePaolo (1981).

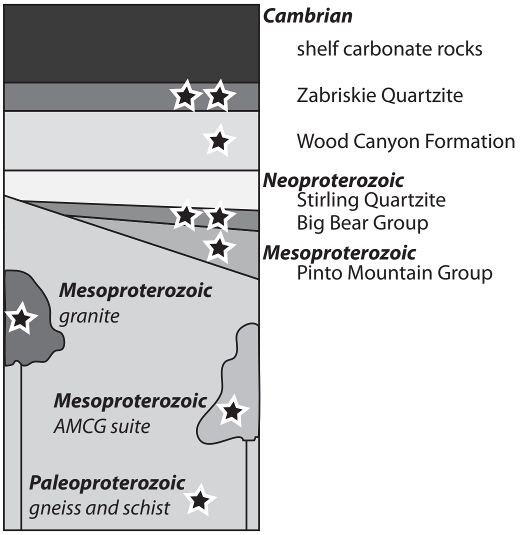

Figure 3. Generalized lithostratigraphic column for Paleoproterozoic basement rocks, Mesoproterozoic intrusions, and sedimentary cover sequences in the southern Mojave crustal province. Sampled lithologic units are indicated by stars. AMCG—anorthosite-mangerite-charnockite-granite.

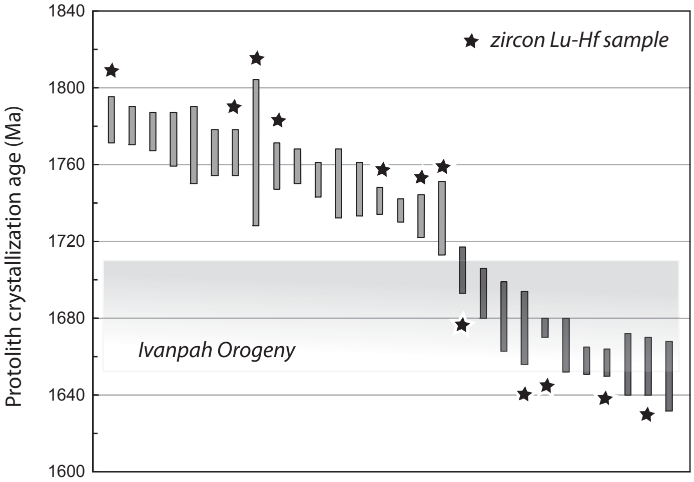

Figure 4. Time series plot of ion microprobe U-Pb zircon crystallization ages of pre-orogenic orthogneisses and post-Ivanpah intrusive rocks in the Paleoproterozoic basement of the southern Mojave province (Barth et al., 2000, 2009; this study). Shaded box illustrates the range of ages of monazites and metamorphic zircon limiting the timing of deformation and high-grade metamorphism during the Ivanpah orogeny. Stars indicate samples with multiple zircon Lu-Hf analyses.

metamorphic episodes at several times between 1.80 and 1.60 Ga: 1.79, 1.76–1.74, 1.71–1.69, and 1.67–1.65 Ga (Barth et al., 2009; Strickland et al., 2009). Field and geochronologic data suggest that regional deformation and metamorphism were most widespread across the province between 1.71 and 1.69 Ga (Ivanpah orogeny of Wooden and Miller, 1990), and were followed by extension and emplacement of relatively alkalic, intermediate to felsic, post-Ivanpah plutons mostly between 1.69 and 1.64 Ga. Post-Ivanpah intrusive rocks are compositionally distinctive and relatively less deformed and metamorphosed in most of the province, suggesting that a profound transition to a thicker and more stable continental crust occurred at about this time (Barth et al., 2009; Strickland et al., 2009).

Paleoproterozoic Mojave province crust was subsequently intruded by two suites of Mesoproterozoic igneous rocks (Fig. 3). Alkalic, syenitic to granitic plutons intruded the northeastern part of the province and range in age between 1.43 and 1.40 Ga (Anderson and Bender, 1989; Gleason et al., 1994). Whole-rock samples from these plutons have initial $^{143}\text{Nd}/^{144}\text{Nd}$ values that lie between those expected of crustal melts and depleted mantle ($\varepsilon_{\text{Nd}} = 0$ to -5; Bennett and DePaolo, 1987; Martin and Walker, 1992; Gleason et al., 1994), a conclusion supported by $^{176}\text{Hf}/^{177}\text{Hf}$ values from bulk dissolution of zircons (Goodge and Vervoort, 2006). The southwestern part of the province was then intruded by plutons of anorthosite, syenite, and granite (the AMCG suite of McLelland et al., 2010), which range in age between 1.21 and 1.18 Ga (Barth et al., 2001; Sparks et al., 2008).

Proterozoic basement rocks of the Mojave province are locally overlain by three discrete Proterozoic to Cambrian siliciclastic sequences (Fig. 3), which mark the stabilization and subsequent rifting of the province: Pinto Mountain Group, Big Bear Group, and the Stirling–Wood Canyon–Zabriskie sequence, deposition of which extended into Cambrian time. The oldest of these three sequences is the Pinto Mountain Group, which is inferred from detrital zircon ages to have been deposited between 1.63 and 1.45 Ga, and may have been coeval with post-tectonic successions in the Yavapai and Mazatzal provinces to the east in southern Laurentia (Barth et al., 2009; Jones et al., 2009). The younger (latest Neoproterozoic to Cambrian), widely dispersed, shelf to miogeoclinal succession is exposed near to and along the Cordilleran hinge line (Stewart and Poole, 1975; Stewart, 1991; Stewart et al., 2001). The far western part of the miogeoclinal succession in the San Bernardino Mountains is locally underlain by a discrete quartzite succession of probable late Neoproterozoic age, the Big Bear Group. Paleocurrent indicators and detrital zircon age spectra for Big Bear Group quartzites are distinct in age and provenance from the overlying Stirling, Wood Canyon, and Zabriskie quartzites (Brown, 1991; Stewart, 2005; Barth et al., 2009).

ANALYTICAL METHODS

Locations and U-Pb ages for the samples analyzed in this study are summarized in Table 1. Individual spot ages for zircons and interpreted crystallization ages for most igneous and meta-igneous rocks were reported by Miller and Wooden (1992), Gleason et al. (1994), Bryant et al. (2001), and Barth et al. (2000, 2001, 2009); zircon spot ages and interpreted crystallization ages for additional samples are reported in Appendix DR1 and Table DR1.[1] Lutetium, hafnium, and ytterbium compositions and isotopic ratios were measured in individual zircons from these samples using the Nu-Plasma laser-ablation, multicollector–inductively coupled plasma–mass spectrometer (ICP-MS) at the University of Florida. Zircons were ablated with a 40-µm-diameter spot on or as near as possible to 30-µm-diameter spots previously analyzed for U-Pb geochronology by ion microprobe, using cathodoluminescence imaging to guide spot selection. Isotopic data were collected in time-resolved analysis mode with online isobaric interference corrections, and data from each ablation were reduced independently as described by Mueller et al. (2008) to ensure isotopic homogeneity of the ablated zircon volume. Measured values for zircon standard FC-1 (uncorrected for its 1100 Ma age) during the period 2004–2011 yielded $^{176}\text{Hf}/^{177}\text{Hf} = 0.28217 \pm 2$ (2σ, $n > 600$) and $\varepsilon_{\text{Hf}}(0) = -24.5 \pm 1.6$ (2σ). The average value for the nonradiogenic $^{180}\text{Hf}/^{177}\text{Hf}$ for the same 600+ analyses deviates from the true value by 0.2 ε, which indicates the contribution from oxide and dimer isobars is negligible. Initial $^{176}\text{Hf}/^{177}\text{Hf}$ values were calculated using Lu/Hf measured during ablation and U-Pb crystallization ages previously calculated for each sample (Table 1). Precision of the final calculated initial isotopic ratios is based on replicate analyses of zircon standard FC-1 and propagation of errors associated with both U-Pb and Lu/Hf measurements. Epsilon values are based on a bulk silicate earth with $^{176}\text{Hf}/^{177}\text{Hf} = 0.282785$ and $^{176}\text{Lu}/^{177}\text{Hf} = 0.0336$ (Bouvier et al., 2008). In a few cases (<<1% of all analyses), high positive epsilon values were calculated that are significantly above the expected value for depleted mantle; these calculated values likely represent an unrecognized mismatch between the U-Pb age domain and the analytical volume sampled for Hf, and are not considered reliable. It is important to note that the calculated $\varepsilon_{\text{Hf}}(T)$ values are much more sensitive to the age assigned to the spot analyzed than to the Lu/Hf used for temporal corrections; e.g., a typical zircon ($^{176}\text{Lu}/^{177}\text{Hf} = 0.001$) will require a correction of only ~1 ε_{Hf} unit per billion years.

RESULTS

Samples of basement rocks and quartzites from cover sequences for which zircon Hf isotope measurements are available are summarized in Table 1. Measured $^{176}\text{Lu}/^{177}\text{Hf}$ and $^{176}\text{Hf}/^{177}\text{Hf}$ values for spots within individual zircons are reported in Tables DR2 and DR3 (see footnote 1). Epsi-

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[1] GSA Data Repository Item 2012298, Zircon Hf isotopic data and additional zircon U-Pb ages, is available at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

TABLE 1. SAMPLE IDENTIFICATION AND Hf MODEL AGES OF ZIRCONS IN MOJAVE PROVINCE BASEMENT ROCKS AND COVER SEQUENCES

Sample	Rock type	U-Pb or stratigraphic age (Ga)	Depleted mantle model age range (Ga)	Location
Cover sequence				
ZAB	Quartzite	Cambrian	–	San Bernardino Mountains[1]
ZBR	Quartzite	Cambrian	–	San Bernardino Mountains[1]
WC	Quartzite	Cambrian	–	San Bernardino Mountains[1]
WQ97-1	Quartzite	Neoproterozoic	–	San Bernardino Mountains[1]
WQ97-2	Quartzite	Neoproterozoic	–	San Bernardino Mountains[1]
JW98-333	Quartzite	Mesoproterozoic	–	Pinto Mountains[1]
Basement rocks				
PCyn	Jotunite pegmatite	1.18	1.33–1.67	San Gabriel Mountains[2]
SGS	Syenite	1.19	1.23–1.57	San Gabriel Mountains[2]
SGA65	Jotunite	1.19	1.32–1.60	San Gabriel Mountains[2]
VP10	Orthogneiss	1.20	1.36–1.66	Eagle Mountains[3]
418-19	Orthogneiss	1.21	1.29–1.58	Eagle Mountains[9]
JW84-4	Granite	1.40	1.68–1.96	Turtle Mountains[6]
EPZ2	Quartz syenite	1.42	1.69–1.90	Barrel Springs, Old Woman Mountains[7]
SGZ	Granite	1.42	1.67–2.09	Piute Mountains[6]
JW89-122	Granite	1.42	1.59–1.97	Yarnell[8]
JW84-13	Granite	1.43	1.68–1.84	Olea Ranch[8]
JW84-15	Granite	1.43	1.71–1.96	Olea Ranch[8]
1168	Granite	1.43	1.69–1.87	Signal[8]
JW149	Granitic gneiss	1.66	1.83–2.09	Pinto Mountains[9]
JW234	Augen gneiss	1.68	2.06–2.26	San Bernardino Mountains[4]
JW85-40	Granodiorite gneiss	1.68	1.82–2.11	Piute Range[5]
JW86-69	Granite	1.68	1.93–2.22	New York Mountains[5]
JW87-85	Granodiorite	1.68	1.89–2.24	New York Mountains[5]
JW87-96	Granodiorite	1.68	1.79–2.21	Old Woman Mountains[5]
JW87-102	Diorite	1.66	1.67–2.31	Old Woman Mountains[1]
JW87-97	Augen gneiss	1.68	1.84–2.44	Old Woman Mountains[1]
418-7	Augen gneiss	1.71	1.73–2.08	Eagle Mountains[9]
JW152	Quartzofeldspathic gneiss	1.74	1.84–2.16	Pinto Mountains[1]
JW86-77	Granodiorite gneiss	1.73	1.69–2.15	New York Mountains[1]
JW87-101	Augen gneiss	1.73	1.93–2.25	Old Woman Mountains[1]
JW87-94	Granitic gneiss	1.76	2.04–2.25	Ivanpah Mountains[5]
JW84-21	Augen gneiss	1.76	2.06–2.74	Ivanpah Mountains[1]
JW87-95	Tonalitic gneiss	1.76	2.02–2.89	Ivanpah Mountains[5]
JW91-172	Trondhjemitic gneiss	1.76	1.71–2.37	Ivanpah Mountains[1]
JW147	Granitic gneiss	1.77	1.86–2.14	Pinto Mountains[9]
JW232	Augen gneiss	1.78	2.07–2.47	San Bernardino Mountains[1]
JW98-330	Quartzite	Paleoproterozoic	1.9–2.3	Pinto Mountains[1]
JW86-79	Garnet gneiss	Paleoproterozoic	1.8–2.6	New York Mountains[1]

Note: References: 1—Barth et al. (2009); 2—Barth et al. (2001); 3—Sparks et al. (2008); 4—Barth et al. (2000); 5—Miller and Wooden (1992); 6—Anderson et al. (1993); 7—Gleason et al. (1994); 8—Bryant et al. (2001); 9—this study.

lon values for both measured ^{176}Hf/^{177}Hf ($\varepsilon_{Hf}[0]$) and initial ratios ($\varepsilon_{Hf}[T]$) are reported relative to the bulk silicate earth in Tables DR2 and DR3, corrected for decay using U-Pb ages of the zircons and Lu/Hf measured by ICP-MS. Depleted mantle model ages (T_{DM}) were calculated using a constant-Lu/Hf-ratio evolution model with present-day depleted mantle ^{176}Hf/^{177}Hf = 0.28324 and ^{176}Lu/^{177}Hf = 0.03871 (Mueller et al., 2008). T_{DM} age ranges for each sample are summarized in Table 1 and reported for individual zircons in Tables DR2 and DR3 (see footnote 1). It is important to recognize that these T_{DM} model ages are based on the Lu/Hf ratios of the zircons, which are invariably lower than bulk or lower crustal values, making the model ages minima. The complex mixing involved in the generation of Mojave crust evident in whole-rock Pb and Nd data likely extends to Hf, and makes choosing an appropriate Lu/Hf value for the source of any particular zircon quite ad hoc. To estimate the magnitude of this effect, we also report two-stage zircon Lu/Hf model ages for magmatic zircons (Table DR2 [see footnote 1]), extrapolating to a model depleted mantle from the calculated initial ^{176}Hf/^{177}Hf using the depleted mantle model as described previously and a model lower crust ^{176}Lu/^{177}Hf = 0.0187 (Rudnick and Gao, 2003).

Hf isotope ratios and model ages described herein are based on interpretations of zircon domains from cathodoluminescence imaging of the sample surface and ion microprobe analysis of trace-element abundances and U/Pb ratios. Orthogneisses and variably foliated, post-Ivanpah intrusive rocks contain zircons that are isotopically and geochemically heterogeneous, with a primary domain characterized by a limited variation in Th/U and a well-defined discordia array that yields an interpreted magmatic zircon crystallization age. Many orthogneisses also contain volumetrically minor (less than 10%) yet isotopically distinct premagmatic Archean and older Paleoproterozoic cores. In metasedimentary rocks, this primary zircon domain yields a wider variation in composition and age that is interpreted to record a detrital zircon population. Zircons in most samples, particularly older orthogneisses and metasedimentary rocks, also contain metamorphic embayments and visible rims, which are characteristically Th depleted, have low Th/U, and often have distinct Hf and rare earth element (REE) abundances. These zircon domains define younger discordia arrays interpreted to reflect later metamorphic recrystallization.

Paleoproterozoic Basement Rocks

The ε_{Hf}(T) values of magmatic zircon from pre-orogenic (1.79–1.73 Ga) orthogneisses and post-Ivanpah (1.69–1.64 Ga) intrusive rocks in the Mojave province vary from +11 to −10. This range in ε_{Hf}(T) values is large, and suites of magmatic zircons from individual samples record 25%–50% of the total observed range (Fig. 5). Because ICP-MS analyses sample a zircon volume that is large compared to ion microprobe analysis, single low values (such as observed in the 1.73 Ga trondhjemitic gneiss; Fig. 5) could be ascribed to analyzing an unexposed premagmatic zircon core below the imaged surface of the magmatic zircon domain. However, the continuity of the data sets for most samples suggests that the observed 5–10 unit range in ε_{Hf}(T) reflects real isotopic variation in magmatic zircons. Similar ranges of initial ε_{Hf} have been observed in both Proterozoic and Phanerozoic magmatic zircons (Andersen et al., 2002; Kemp et al., 2007; Shaw and Flood, 2009; Foster et al., 2012).

Magmatic zircons in the orthogneisses and intrusive rocks range downward from values approximating those expected for melts derived from Paleoproterozoic depleted mantle (Fig. 6). Magmatic zircons from the older orthogneisses (ε_{Hf}[T] of +11 to −8) and post-Ivanpah intrusive rocks (ε_{Hf}[T] of +10 to −10) yield virtually identical ranges in initial isotopic compositions, and these ranges suggest that both depleted mantle (ε_{Hf} ~9–11 at 1.7 Ga) and enriched sources played a role in petrogenesis. This wide variation in initial Hf ratios is compatible with Nd T_{DM} model ages that range from 1.67 to 2.88 Ga and average ca. 2.1 Ga. This observation reinforces prior interpretations that whole-rock Nd model ages reflect the influence of both juvenile and recycled crustal material in Paleoproterozoic crust formation (e.g., Bennett and DePaolo, 1987).

The isotopic composition of detrital zircons in sediment delivered directly into the evolving Mojave province prior to and during the early stages of orogenic crust formation reflects the compositional maturity of their source rocks. Detrital zircons from pre-orogenic garnet gneiss (metagraywacke) and quartzite have ε_{Hf}(T) ranging from +9 to −9 at 1.8–1.9 Ga; older zircons show progressively less variation (e.g., +4 to −4 at 2.6 Ga; Fig. 6). Detrital zircons in the metagraywacke are dominated by older Paleoproterozoic and Late Archean ages with ε_{Hf} ~0 ± 5. The ε_{Hf}(T) values show increasing dispersion with decreasing U-Pb age, with the youngest zircons yielding ε_{Hf}(T) of −5 to −9, as low as the lowest magmatic zircons in orthogneisses. Detrital zircons from the quartzite have ages and isotopic compositions that fall within the range of values defined by pre-orogenic felsic orthogneisses, suggesting local derivation during the early stages of arc magmatism.

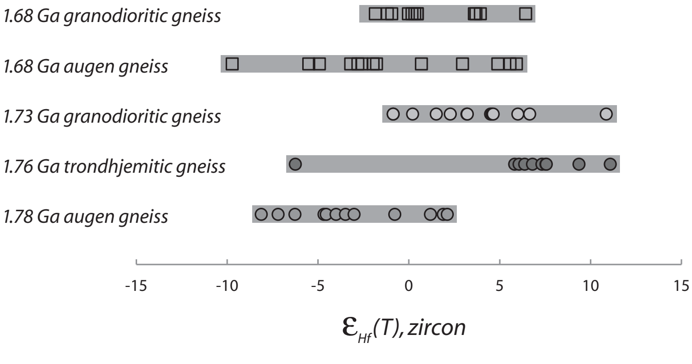

Figure 5. Representative range in magmatic zircon ε_{Hf}(T) values from Paleoproterozoic orthogneisses in the Mojave province. Points represent zircon spot analyses, and bars encompass the range of zircon isotope ratios in a given whole-rock sample.

Mesoproterozoic Granites and AMCG Suite

The ε_{Hf}(T) values of magmatic zircons from ca. 1.42 Ga granites and the ca. 1.2 Ga AMCG suite reflect intracontinental magma sources and magmatic processes in the Mojave province portion of Laurentia following Paleoproterozoic crust formation (Fig. 7). Alkalic granites with ages of ca. 1.42 Ga yield zircons with a total observed range of ε_{Hf}(T) from +5 to −6. The average value of 0.7 ± 2.5 for 69 measurements is in agreement with the Hf isotopic compositions of bulk zircon fractions from these granites reported by Goodge and Vervoort (2006). Suites of magmatic zircons from individual samples record nearly the total observed range for all seven samples we measured; for example, the granite from the Piute Mountains contains magmatic zircons that range from +4.4 to −6.1. The average ε_{Hf}(T) of zircons from these younger granites is similar to zircons from 1.64 to 1.8 Ga basement rocks, and both age suites show a significant range of values, although the observed range is somewhat smaller for the younger intrusive suite.

We also measured the Hf isotopic composition of zircons from a jotunite, a jotunite pegmatite, a syenite, and two granitic gneisses from the ca. 1.2 Ga Mojave province AMCG suite in the San Gabriel and Eagle Mountains (Figs. 1 and 7). As observed for the older Mesoproterozoic granites, these zircons have a wide range of initial ε_{Hf} values, though ε_{Hf}(T) values in the AMCG suite zircons are consistently higher (−1 to +11). Zircons from the syenite and jotunite define the range for these Mesoproterozoic magmas, with the upper end of this range largely overlapping the original ion microprobe Hf measurements of the jotunite pegmatite by Kinny et al. (1991). The zircons from the granitic gneisses show a range of values that is not significantly different, ranging from 0 to +9. In general, zircons from the ca. 1.2 Ga AMCG suite show similar dispersion but more positive average initial values than zircons from the ca. 1.42 Ga granites.

Detrital Zircons in Siliciclastic Cover Sequences

Detrital zircons in siliciclastic cover sequences may reflect the age and isotopic character of zircons in Mojave province basement, and/or they may record the influx of zircons from distal sources, which may help constrain the time of docking of the Mojave province to Laurentia. The initial ε_{Hf} values of detrital zircons, plotted at their measured U-Pb ages, indicate a wider range of ages and isotopic compositions than exposed basement rocks and, therefore, may provide insight into a provenance that is not currently exposed, or a more distal provenance reflecting influx of sediment from other crustal provinces (Figs. 8 and 9). The least complex data are from quartzites of the Pinto Mountain Group, which have nearly unimodal detrital zircon age spectra. In these samples, initial Hf isotopic compositions range from +11 to −9, closely matching the local orthogneisses and the local metasedimentary basement rocks in age and Hf isotopic composition (Fig. 8).

In contrast, detrital zircons in quartzites from the Big Bear Group have a wider range of U-Pb ages, and their Hf isotopic compositions are a poor match for local basement sources, as previously inferred (Barth et al., 2009) from the distribution of detrital zircon ages alone (Fig. 8). Zircons from the Big Bear Group include three dominant age populations.

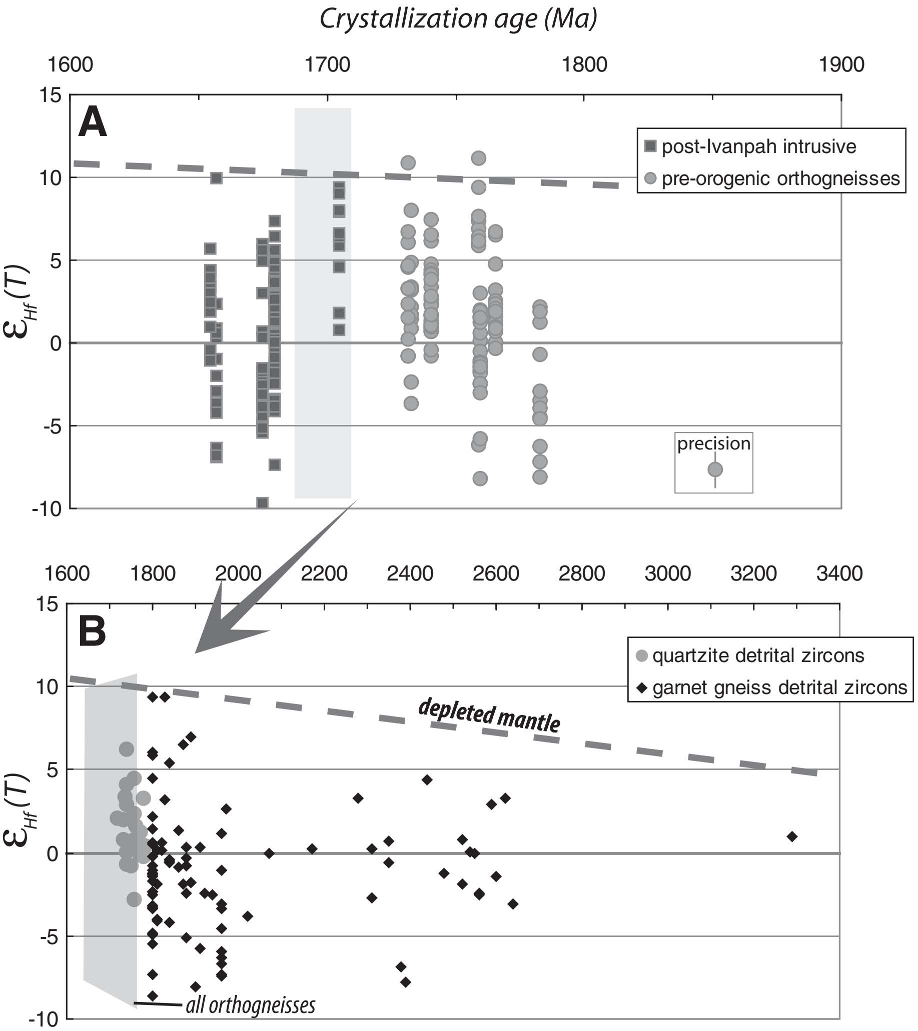

Figure 6. Hf analyses of zircons in older basement rocks of the Mojave province. Points represent zircon spot analyses, plotted as crystallization age versus ε_{Hf}(T). (A) Zircons from pre-orogenic orthogneisses (filled circles), and zircons from post-Ivanpah intrusive rocks (filled boxes). Dashed line is the Hf evolution curve for model depleted mantle, and shaded box is the peak age range of the Ivanpah orogeny. Note that three more negative values are not plotted at this scale. (B) Detrital zircons from pre-orogenic quartzite and garnet gneiss (metagraywacke) compared to the data range of igneous protoliths from A (shaded box). Dashed line is the ε_{Hf} evolution curve for model depleted mantle.

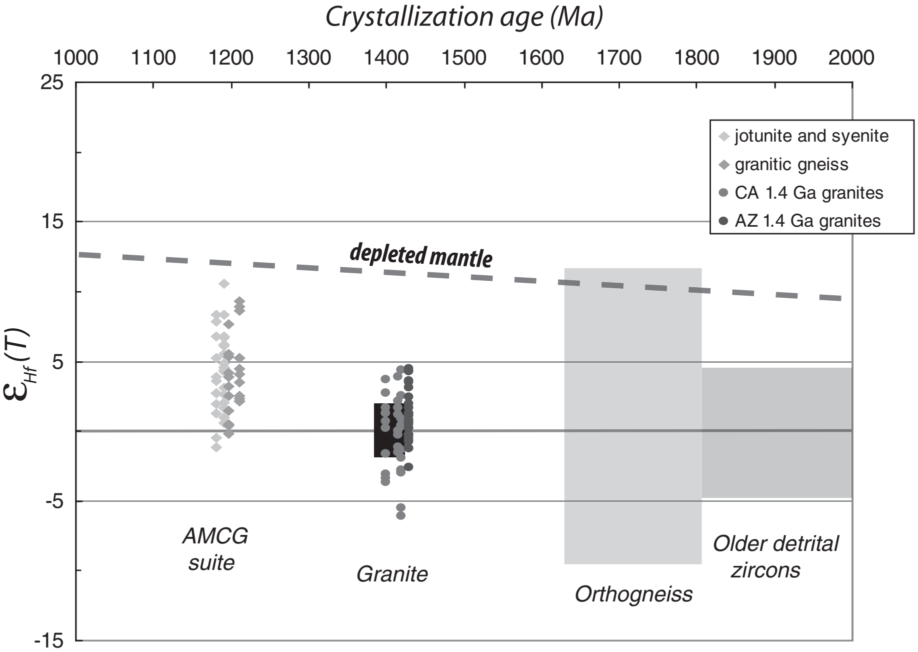

Figure 7. Hf analyses of younger Mesoproterozoic granite and AMCG suite plutons, compared to older basement rocks of the Mojave province. Points represent spot analyses within individual zircons, plotted as U-Pb zircon crystallization age versus ε_{Hf}(T). Dashed line is the Hf evolution curve for model depleted mantle. Shaded boxes represent the range of ages and isotopic compositions of basement rocks and detrital zircons in older gneisses that host these younger plutons, from Figure 6. For comparison, dark shaded field at ca. 1400 Ma represents range of bulk isotopic analyses of zircons from ca. 1.4 Ga granites (Goodge and Vervoort, 2006). AMCG—anorthosite-mangerite-charnockite-granite.

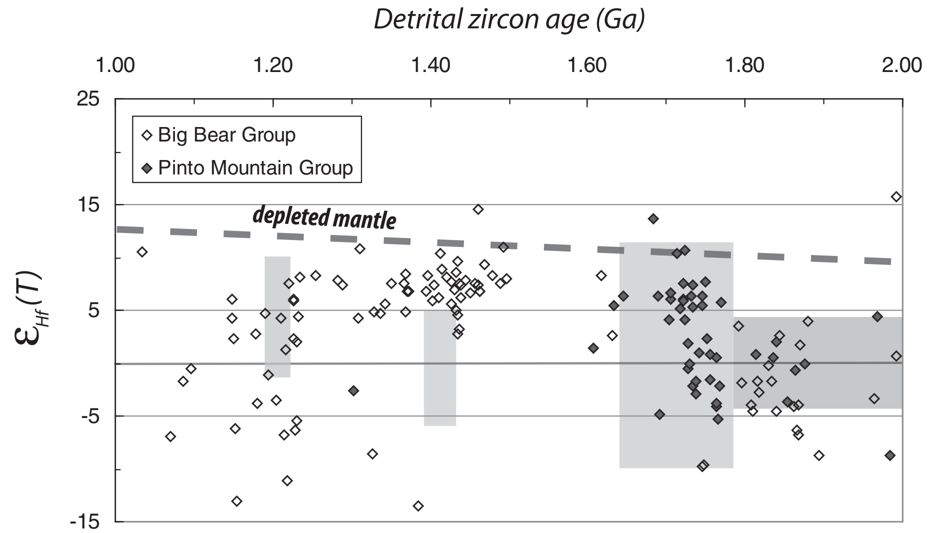

Figure 8. Hf analyses of spots within individual detrital zircons from siliciclastic cover sequences overlying southern Mojave province basement, plotted as measured U-Pb zircon age versus ε_{Hf}(T). Plotted are zircons from Mesoproterozoic Pinto Mountain Group quartzite (filled symbols) and zircons from quartzites in the Neoproterozoic Big Bear Group (open symbols). Shaded boxes illustrate the range in U-Pb zircon age and ε_{Hf}(T) of zircons from Paleoproterozoic to Mesoproterozoic basement of the southern Mojave province, which underlies these rift sequences, from Figures 6 and 7. AMCG—anorthosite-mangerite-charnockite-granite.

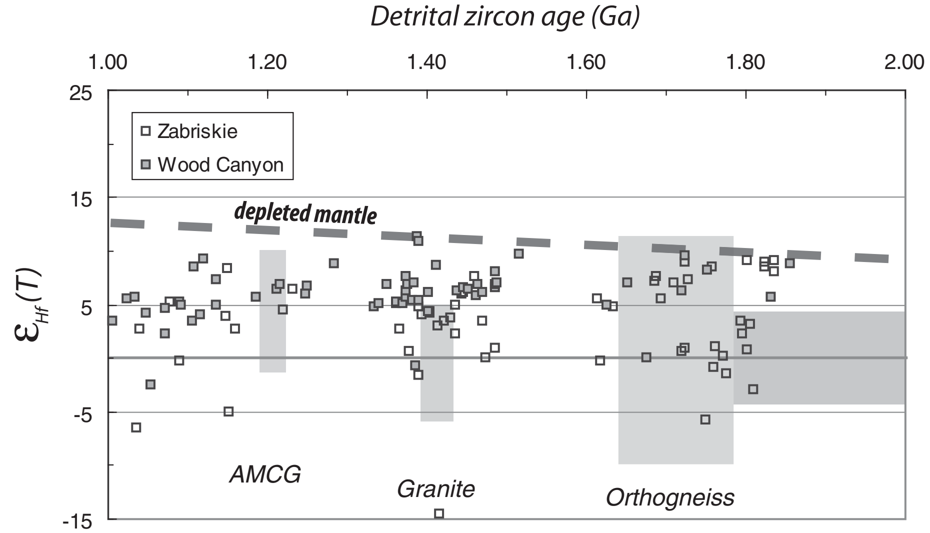

Figure 9. Hf analyses of spots within individual detrital zircons from cratonal cover sequences overlying southern Mojave province basement, plotted as measured U-Pb zircon age versus ε_{Hf}(T). Plotted are zircons from latest Neoproterozoic to Cambrian Wood Canyon Formation (filled symbols) and Cambrian Zabriskie Quartzite (unfilled symbols). Shaded boxes illustrate the range in U-Pb zircon age and ε_{Hf}(T) of zircons from Paleoproterozoic to Mesoproterozoic basement of the southern Mojave province, which underlies the cratonal cover sequence, from Figures 6 and 7. AMCG—anorthosite-mangerite-charnockite-granite.

The oldest zircons are primarily ≥1.8 Ga in age and have ε_{Hf} similar to detrital zircons in Mojave province metasedimentary basement rocks. In stark contrast to the Pinto Mountain Group, virtually no zircons similar to those from basement orthogneisses or post-Ivanpah intrusive rocks are observed. Zircons in the intermediate age group are mostly 1.45–1.39 Ga, i.e., broadly similar in age to Mojave province Mesoproterozoic granites, but ε_{Hf} of +5 to +10 shows little overlap. The youngest age group of zircons ranges from 1.26 to 1.1 Ga with very diverse ε_{Hf} values of +8 to –15.

Detrital zircons in quartzites from the Zabriskie Quartzite and Wood Canyon Formation of the Neoproterozoic to Cambrian siliciclastic cover sequence show some similarities to the underlying Big Bear Group, but strong mismatches with local basement sources (Fig. 9; Stewart et al., 2001; Barth et al., 2009). The Zabriskie and Wood Canyon quartzites contain three dominant zircon age populations. The oldest zircons are primarily 1.61–1.84 Ga in age and have ε_{Hf} of +5 to +10, which is similar only to relatively high ε_{Hf} zircons in Mojave province basement rocks. Zircons in the intermediate age group are mostly 1.49–1.35 Ga, with a wider range in age and typically higher ε_{Hf} than Mojave province Mesoproterozoic granites. Zircons in the youngest age group are mostly 1.25–0.94 Ga with ε_{Hf} of +3 to +10.

DISCUSSION

Crust Formation Processes Inferred from Hf Isotopes in Basement Zircons

The extent of Paleoproterozoic crust in the Mojave province is defined by Sm-Nd model ages of whole rocks, which range from 2.7 to 1.7 Ga and average ca. 2.2 Ga (e.g., Bennett and DePaolo, 1987; Fig. 2). These model ages imply recycling of older crustal materials during formation of the exposed crust of the province (Bennett and DePaolo, 1987; Rämö and Calzia, 1998; Coleman et al., 2002), yet the identity and mechanism of recycling these older components are ambiguous in the bulk-rock data. Hf isotopic analyses of zircon domains of known U-Pb age shed considerable light on the timing and means of incorporation of geochemically distinct components assembled to form the Mojave province.

Zircon geochronology in conjunction with Hf isotopic data indicate that the Mojave province was assembled in a long-lived convergent margin environment characterized by early calc-alkalic arc plutonism, between ca. 1.79 and 1.73 Ga, and continued with relatively felsic and potassic post-Ivanpah plutonism between 1.69 and 1.64 Ga. The early stages of this later felsic and potassic magmatism were spatially and temporally associated with high-grade metamorphism, crustal thickening, and, locally, with late, top-to-the-west extension. The Hf isotopic variability of zircons from these intrusive rocks records crystallization from melts with diverse isotopic components (Figs. 6 and 10). Diversity in observed isotopic compositions characterizes all the plutons analyzed for this study, intruded over a time span of more than 600 m.y. This implies that mixing of melts representing distinct reservoirs was the dominant process by which these plutonic rocks were formed, as indicated by the ranges of $\varepsilon_{Hf}(T)$ and Hf T_{DM} ages in magmatic zircons from individual samples.

Hafnium depleted mantle model ages are single-stage ages calculated using measured Lu/Hf ratios, and are therefore likely to represent minimum ages of crust extraction from a depleted mantle. Somewhat more realistic crust extraction ages may be estimated using a two-stage model (Tcr[2] in Table DR2 [see footnote 1]). The choice of an average parent/daughter ratio for a reasonable first evolutionary stage is somewhat ambiguous, given a likely role for both a comparatively depleted mantle component, as represented by 1.76 Ga zircons with T_{DM} ages of 1.71–1.91 Ga in the trondhjemitic gneiss, and preexisting crustal components with lower Lu/Hf ratios. We modeled this mixture assuming early Hf isotopic evolution in a simple crustal reservoir with a bulk lower-crustal Lu/Hf. The resulting Tcr(2) model ages are typically 150–500 m.y. older than single-stage Hf T_{DM} ages, intersecting the model depleted mantle at ages of 2.0–2.9 Ga. The zircon Hf isotopic data, therefore, suggest ultimate derivation of Mojave province orthogneisses and granitic rocks from Neoarchean crust variably mixed with comparatively depleted, mantle-derived magmas with high Lu/Hf.

In addition, when the Hf isotopic compositions of zircons from basement intrusive rocks are compared to those of metasedimentary framework rocks of the province, it is evident that additional components are required to generate a more complete model of crustal evolution. Detrital zircons in pre-orogenic metagraywacke and quartzite suggest that two principal older crustal components were physically mixed: (1) a Paleoproterozoic (2.0–1.8 Ga) arc terrane built on continental crust with ε_{Hf} +7 to −8, and (2) a compositionally similar, Neoarchean (2.6–2.4 Ga) craton. These two main older crustal components provided melts during orogenesis that mixed with melts from both depleted and modestly enriched mantle to form the framework rocks of the province. Mixing of melts from isotopically similar lower crust and upper mantle in the source regions of 1.79–1.64 Ga magmas is indicated by magmatic zircons with ε_{Hf} from +11 to −9 (Figs. 6 and 10). The inferred presence of comparatively enriched mantle is based on the compositions of amphibolites with low initial ^{143}Nd/^{144}Nd ratios at 1.81 Ga (Fig. 2) and by evidence from Nd and Os isotopes of the continued presence of this enriched mantle beneath the Mojave province until Tertiary time (e.g., Farmer et al., 1989, 1995; Lee et al., 2001). It should also be noted that a Neoarchean reservoir with modestly high U/Pb and Th/Pb ratios (with respect to an average crust model such as Stacey and Kramers, 1975) is one possible model to explain the enriched common Pb isotopic signature of the Mojave crustal province (Wooden et al., 1988). Although not an exclusive model, mixing with an enriched Neoarchean reservoir could, therefore, explain observed Hf, U-Th-Pb, and Nd isotopic systematics in the Mojave crustal province.

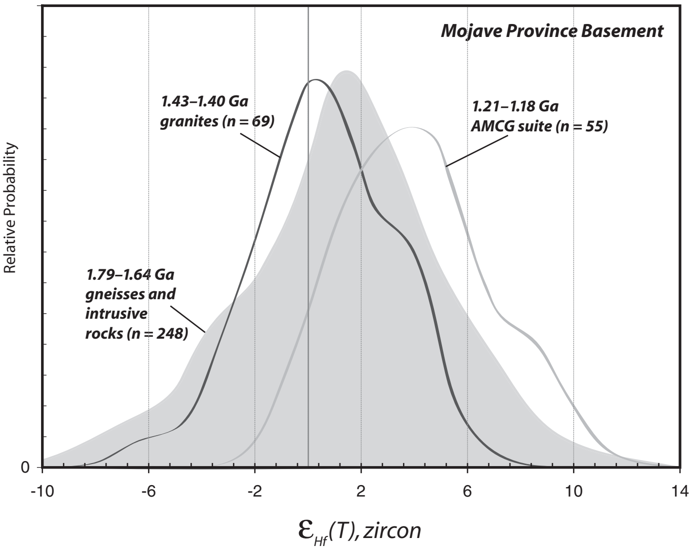

Figure 10. Probability plot of Hf isotopic compositions of zircons from the three major age components of the crystalline basement of the Mojave province. AMCG—anorthosite-mangerite-charnockite-granite.

Using these data to place limits on the likely relationship between the Mojave province and older crust is critical to understanding the assembly of this part of Laurentia. The most proximal potential source of older material lies to the northeast in the Wyoming craton (Mueller and Frost, 2006; Mueller et al., 2010). Although the oldest, 2.7–2.6 Ga Nd model ages of Mojave province basement rocks may be taken to indicate the *minimum* age of Mojave province lithosphere, physical evidence for the presence of any significantly older crust is very limited, as remarkably few zircons older than ca. 2.6 Ga have been reported. Thus, although there are important geochemical similarities between Mojave and Wyoming province lithosphere (e.g., U-Th-Pb systematics), the paucity of 2.7 Ga and older zircons in the Mojave province suggests that physical mixing of Wyoming province crust into the nascent Mojave province was very limited (e.g., Mueller et al., 2011). Alternatively, the 2.6–2.4 and 2.0–1.8 Ga components may have been derived from an unexposed part of the Mojave province (Whitmeyer and Karlstrom, 2007), or an older crustal block that lay to the west (Barth et al., 2009).

Later Proterozoic Crustal Evolution of the Mojave Province

The Paleoproterozoic crust of the Mojave province was intruded by a diverse suite of mafic to granitic magmas in Mesoproterozoic time, including 1.43–1.40 Ga syenites and granites and a 1.21–1.18 Ga AMCG suite. Previous workers favored partial melting of deep crustal rocks of mafic to quartzofeldspathic composition to generate the ca. 1.42 Ga syenitic and granitic magmas, respectively (Anderson and Bender, 1989; Gleason et al., 1994), and Ekstrom et al. (1994) favored a similar model for generation of jotunite, mangerite, and syenite of the ca. 1.2 Ga AMCG suite. The $\varepsilon_{Hf}(T)$ values of zircons from the ca. 1.42 Ga syenites and granites are numerically similar to zircons from 1.8 to 1.64 Ga basement rocks, but they are not petrologically equivalent because of the 300 m.y. difference in their emplacement ages (Fig. 10). The reduction in the range of ε_{Hf} values relative to older Mojave crust is suggestive of greater homogenization of mantle and crustal components, but it does not require the introduction of new sources. In the context of this model, it may be significant that none of the measured zircons yielded initial ε_{Hf} values close to depleted mantle (a T_{DM} close to 1.42 Ga). There is thus little direct evidence for an undiluted depleted mantle contribution to these magmas. What cannot be ruled out, however, is involvement of an enriched lithospheric mantle and/or lower crust characterized by relatively low Lu/Hf and Sm/Nd, as reported in many subcontinental lithospheric mantle reservoirs (O'Reilly and Griffin, 2006).

Important similarities and differences are evident in the Hf systematics of zircons from the younger Mesoproterozoic rocks of the AMCG suite.

The range of initial Hf isotopic compositions is similar to what is observed in zircons from 1.42 Ga rocks, but the average composition is shifted toward more positive ε_{Hf} (Fig. 10). These data suggest mixing of Mojave crust with mantle characterized by higher ε_{Hf}, or melting of enriched mantle to form jotunite and syenite (and anorthosite), and subsequent melting of crust to form the associated granites (e.g., Bickford et al., 2010). It seems clear that a significant change in magma sources occurred between 1.42 and 1.2 Ga. If the lower-crustal source regions were similar, the more positive ε_{Hf} indicates a greater involvement of asthenospheric mantle in lithospheric additions during the AMCG magmatic episode at 1.2 Ga.

Quartzite Provenance from U-Pb Ages and Hf Isotopes of Detrital Zircons

In addition to information on magma genesis and crust formation, coupled U-Pb age and Lu-Hf isotope systematics of detrital zircons are useful to characterize the provenance of siliciclastic sediment deposited on Mojave province crust. Detrital zircon age spectra are a primary tool for provenance interpretation of siliciclastic rocks in crustal cover sequences in southwestern Laurentia (Gehrels et al., 1995, 2011; Stewart et al., 2001; Barth et al., 2009), in some cases supported by bulk-rock Nd isotope compositions (Farmer and Ball, 1997). The recognized provinciality of Nd in basement rocks of southwestern Laurentia (Farmer and DePaolo, 1983; Bennett and DePaolo, 1987) suggests that the geochemically analogous Hf isotopic system in zircon could provide a similar, yet more detailed test of sediment provenance inferences derived from zircon age spectra, and help clarify nonunique interpretations based on age data alone. This is illustrated by the data for the Paleoproterozoic metasedimentary framework rocks described previously, which record the age and isotopic character of detrital inputs into the nascent Mojave province. However, a suitably comprehensive reference database of age and Hf isotopic composition of North American Proterozoic basement rocks does not yet exist and must be built for such coupled U-Pb and Hf studies to fully succeed. Here, we use the coupled U-Pb and Hf measurements to assess the insularity of the Mojave province during Mesoproterozoic to Cambrian siliciclastic sedimentation as recorded by the age and isotopic diversity of detrital zircons.

This study shows that three Proterozoic to Cambrian siliciclastic cover sequences on the Mojave province have distinctive zircon age and isotopic spectra that illuminate extra-provincial sediment influxes (Fig. 11). Four samples of quartzite from the Mesoproterozoic Pinto Mountain group yielded zircons with very similar ages that define a single population with a peak age of ca. 1.73 Ga. In contrast, basal quartzites of the Neoproterozoic Big Bear Group yield three main populations with peak ages of ca. 1.86 Ga, 1.45 Ga, and 1.2 Ga. Latest Neoproterozoic to Cambrian marginal miogeoclinal quartzites from the Wood Canyon Formation and Zabriskie Quartzite also yield three main populations, but with discrete age peaks at ca. 1.78 Ga, 1.42 Ga, and 1.1 Ga. These latter two sequences represent sediment derived from (perhaps unexposed) Mojave province crust or sediment delivered to the Mojave province subsequent to its incorporation into Laurentia; these age spectra are compared to the range of zircon ages in underlying Mojave province crust in Figure 11.

The oldest of the cover sequences, the Pinto Mountain Group, was deposited after 1.63 Ga, on the basis of observed detrital zircon ages (Barth et al., 2009). The minimum depositional age is not well constrained, but the lack of ca. 1.4 Ga detrital zircons suggests a depositional age older than ca. 1.45 Ga. The detrital zircons are strikingly similar in age and Hf isotopic composition to local Mojave province basement rocks (Figs. 8 and 11). This sequence of quartzite, pelitic schist, and dolomitic carbonate rocks may be interpreted as deposits of a shallow-marine intracratonic basin, and the limited range of zircon ages and their isotopic similarity to local basement rocks suggest deposition in an intracratonic basin, perhaps formed by postorogenic rifting. Such mature quartzite successions are widely distributed across southwestern Laurentia (Cox et al., 2002; Jones et al., 2009) and may mark a regional episode of crustal stabilization following accretion of the Yavapai and Mojave provinces. The similarity in Hf isotopic data of Pinto Mountain Group zircons to zircons from basement rocks also provides further support for the hypothesis that the basement rock zircon isotopic data adequately represent the isotopic character of Mojave province basement rocks of this age.

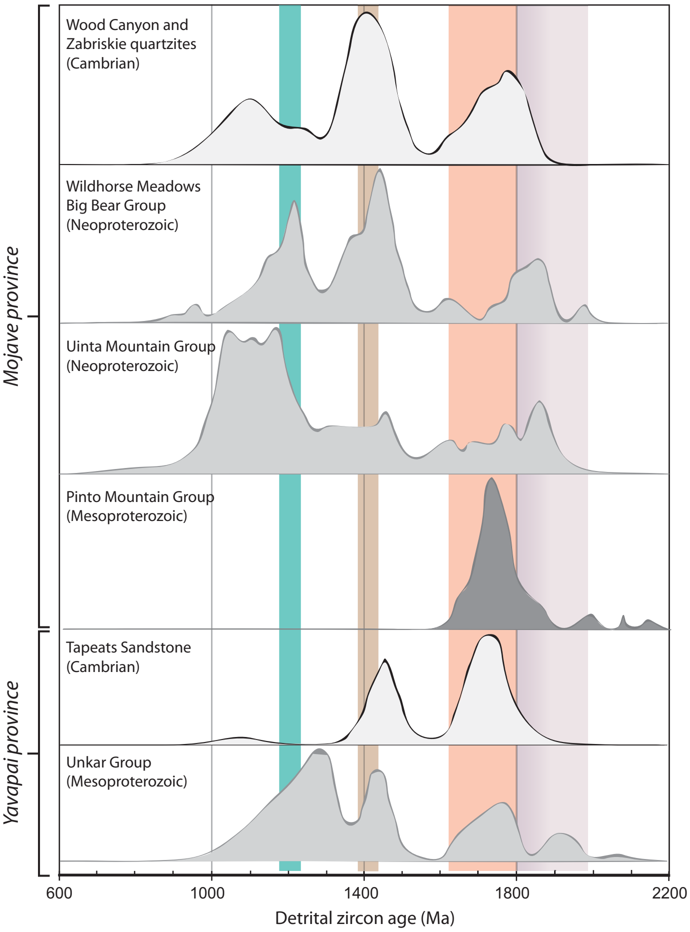

Figure 11. Summary plot of detrital zircon age spectra from quartzite cover sequences deposited on Mojave province basement (Mueller et al., 2007; Barth et al., 2009; Dehler et al., 2010). Zircon age spectra from cover sequences on Yavapai province basement in Arizona are shown for comparison (Timmons et al., 2005; Gehrels et al., 2011). Shaded boxes illustrate the range in U-Pb ages of zircons from Proterozoic basement of the southern Mojave province.

Zircons in the younger Neoproterozoic cover sequence, the Big Bear Group, contrast sharply with the Pinto Mountain Group in age range and isotopic diversity (Fig. 11), and the combination of ages and the range of Hf isotopic compositions of age populations suggest possible sources for this quartz-rich sediment (Figs. 12 and 13). The oldest group of zircons are older than 1.8 Ga, and very few zircons fall in the 1.79–1.64 age range typical of local Mojave province basement and the predominant age population in the Pinto Mountain Group. Nevertheless, $\varepsilon_{Hf}(T)$ values in these older detrital zircons are similar to detrital zircons in Mojave province metagraywacke, consistent with derivation from an isotopically similar 2.0–1.8 Ga terrane. The ca. 1.47–1.37 Ga and 1.3–0.9 Ga detrital zircon populations

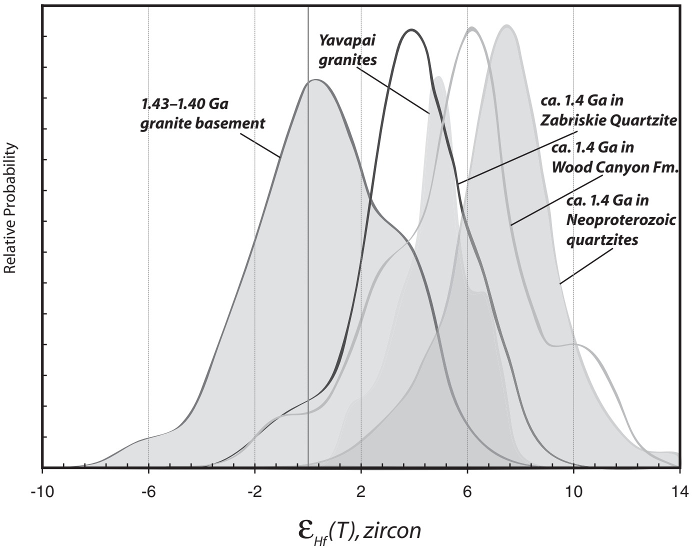

Figure 12. Probability plot of Hf isotopic compositions of zircons from Mesoproterozoic granites of the Mojave province compared to Mesoproterozoic detrital zircons in quartzites from the Neoproterozoic and Cambrian cover sequences (additional data from Gehrels and Pecha, 2012, personal commun.). Bulk zircon ε_{Hf} values in Yavapai province Mesoproterozoic granites are shown for comparison (Goodge and Vervoort, 2006). Note that the ca. 1.4 Ga detrital zircons in the Neoproterozoic quartzites have a low probability of having been derived from Mojave province basement of the same age, but that broadening and shifting of the probability distributions suggest a greater similarity between ca. 1.4 Ga detrital zircons in Cambrian quartzites and zircons from Yavapai province granitic basement.

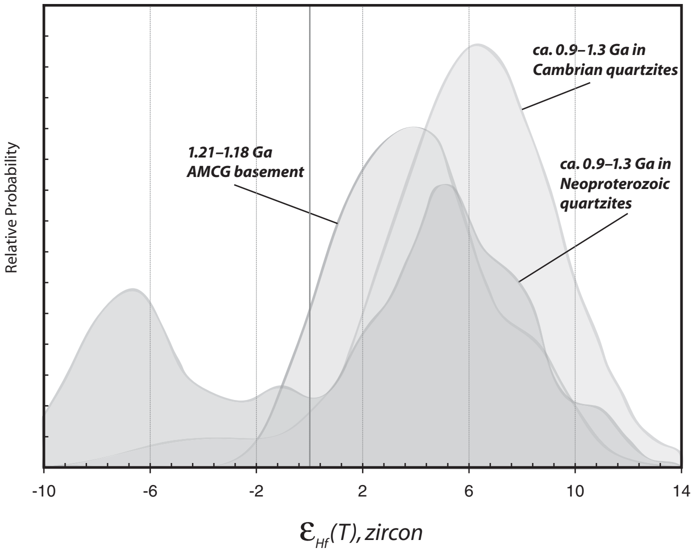

Figure 13. Probability plot of Hf isotopic compositions of zircons from late Mesoproterozoic AMCG (anorthosite-mangerite-charnockite-granite) suite rocks of the Mojave province compared to late Mesoproterozoic detrital zircons in quartzites from the Neoproterozoic and Cambrian cover sequences (additional data from Gehrels and Pecha, 2012, personal commun.). Note the broader age distribution among the detrital zircons, and also the overall similarity in probability distributions between detrital zircons in Neoproterozoic and Cambrian quartzites.

are more chronologically diverse than exposed Mesoproterozoic basement rocks, and zircons in both of these age populations have ε_{Hf}(T) values that are isotopically distinct from zircons of comparable age in the basement rocks. Big Bear Group detrital zircons of ca. 1.4 Ga age have significantly higher ε_{Hf}(T) values than basement zircons, with values of +5 to +10 most commonly observed, whereas values greater than +5 have not been observed in Mojave granites of this age (Fig. 12). These probability distributions strongly suggest that the detrital zircons in the Big Bear Group quartzites were not derived from Mojave or Yavapai province basement rocks. The youngest population of Big Bear Group detrital zircons is more diverse in age and in ε_{Hf}(T) than zircons from the AMCG suite (Fig. 13).

These data clearly exclude exposed Mojave province crust as a source for Big Bear Group sediments, and they provide age and Hf isotopic limits on its provenance region or regions, dependent on the likely direction of sediment derivation. The Big Bear Group underlies inner-shelf miogeoclinal sedimentary rocks and has been interpreted either as a Neoproterozoic early miogeoclinal succession (Cameron, 1982) or as a Rodinian (Mesoproterozoic to Neoproterozoic) rift succession (Stewart, 2005). Quartzites in the lower Big Bear Group have paleocurrent structures indicative of sediment derivation from the south and west, i.e., opposite to paleocurrent data in overlying miogeoclinal rocks, and these lower quartzites are overlain by quartzite and phyllite with tidal sedimentary structures (Cameron, 1982; Stewart, 2005). Cameron interpreted the entire Big Bear Group as having been deposited on a tidally influenced shallow-marine shelf, whereas Stewart interpreted the cross-bedded quartzites with predominantly south and west paleocurrent indicators as intervals of eolian deposition in an otherwise marginal marine setting.

These observations and sedimentologic interpretations lead to two possible provenance hypotheses for Big Bear Group zircons, depending on the ultimate derivation of these quartzites. If the Big Bear Group represents west-derived sediment of an early shallow-marine rift phase of the miogeocline, the presence of pre–1.8 Ga detrital zircons and general lack of 1.79–1.64 Ga detrital zircons suggest the source of the Big Bear Group was an unexposed subprovince of the Mojave province. This hypothesis is suggested by the observed Hf isotopic similarity of the oldest detrital zircon component to zircons in Mojave province metasedimentary basement rocks, but there is no evidence from detrital zircons that this hypothesized subprovince experienced ca. 1.7 Ga magmatism and crustal thickening. The characteristics of Mesoproterozoic detrital zircon populations indicate that this hypothetical western Mojave subprovince crust would also have been intruded by Mesoproterozoic Laurentian plutons, albeit somewhat older and with lower average ε_{Hf} than Mesoproterozoic plutons in exposed Mojave province crust, and it would have been overprinted by Grenville orogenesis (Fig. 8).

Existence of this hypothesized western provenance implies that Big Bear Group detritus was shed onto Laurentia from its conjugate rift pair within Rodinia early in the evolution of the Cordilleran miogeocline (Coleman et al., 2002; Barth et al., 2009). Goodge et al. (2008) recently recovered a 1.43 Ga granite clast from glacial till in the Transantarctic Mountains and suggested the clast may indicate a tie between this basement of the Transantarctic Mountains region and Laurentia. Although the Nd and Hf isotopic characteristics of this clast are inconsistent with an origin in basement in close proximity to the Mojave province, its zircon ε_{Hf} of +7 is broadly similar to granites of the southeastern Granite-Rhyolite province of Laurentia and is remarkably similar to the hypothesized western source of the Big Bear Group ca. 1.45 Ga detrital zircons (cf. Fig. 12). These comparisons indicate the utility of more analyses of this type to test and refine Rodinia reconstructions based on basement rocks and detrital zircons in basement cover sequences in western Laurentia.

Alternatively, if the cross-bedded quartzites are eolian, and predominant paleoflow directions do not record ultimate sediment derivation, the Big

Bear Group may have been derived from a Hudsonian-Grenville terrane in eastern Laurentia. In this hypothesis, it is difficult to envision a transcontinental sediment transport that would not incorporate more Archean and ca. 1.7 Ga zircons, as has been suggested for the east-derived component of sediment in the Neoproterozoic Uinta Mountain Group (Mueller et al., 2007; Dehler et al., 2010). More Hf isotopic data on basement rocks in the Yavapai and Mazatzal provinces and in southern Laurentia are clearly needed, but we suggest that these initial data may be consistent with transcontinental sediment transport and a source relatively far to the east and south, probably within the southern Granite-Rhyolite province and its basement and the adjacent Precordillera terrane, which had not yet rifted away from southern Laurentia at this time (Thomas and Astini, 1996).

The Neoproterozoic Big Bear Group in the San Bernardino Mountains is overlain by siliciclastic and carbonate rocks of the Cordilleran miogeocline. The marginal miogeoclinal Wood Canyon Formation and Zabriskie Quartzite were deposited on both the Big Bear Group and directly on Mojave province basement, and are linked stratigraphically and by detrital zircon geochronology to correlative cratonal units, including the Tapeats Sandstone of the Colorado Plateau (Stewart and Poole, 1975; Stewart et al., 2001). The age spectra for our Cambrian samples from the southern miogeocline are similar to ages reported by Gehrels et al. (2011) for zircons from the Tapeats Sandstone in the Grand Canyon (Fig. 11). While the older age peaks for these Cambrian samples are broadly consistent with derivation from underlying Paleoproterozoic rocks, as concluded by previous workers, our $\varepsilon_{\mathrm{Hf}}$ data indicate a poor fit to local Paleoproterozoic and Mesoproterozoic granitic basement (Figs. 12 and 13). Detrital zircons of ca. 1.4 Ga age have significantly higher $\varepsilon_{\mathrm{Hf}}$ than Mojave basement zircons, yet when compared to the underlying Big Bear Group, the detrital zircons are shifted toward more negative values that are more consistent with derivation from a Yavapai-like Mesoproterozoic granitic source rock (Goodge and Vervoort, 2006; Fig. 12). The ca. 0.9–1.3 Ga zircon population is more diverse in age and in $\varepsilon_{\mathrm{Hf}}$ compared to basement zircons from the AMCG suite, but it is isotopically similar to detrital zircons of similar age in the underlying Big Bear Group. These initial data could be consistent with transcontinental sediment transport and a provenance that was shifting relatively toward the continental interior as the miogeocline became regionally well established in Cambrian time (Gehrels et al., 2011).

CONCLUSIONS

In this study, Hf isotopic data from zircons of known crystallization age are shown to be useful to quantify isotopic diversity in framework sedimentary rocks and melts associated with crust formation in the Mojave crustal province, as well as zircons delivered to the Mojave crustal province subsequent to its incorporation into Laurentia. U-Pb and Hf isotopic data suggest that crust with the characteristic Pb and Nd whole-rock isotopic signature of the Mojave province formed by mixing among depleted mantle, enriched mantle, and both melts and tectonic slices of 2.0–1.8 and 2.6–2.4 Ga rocks. Comparison of these results to detrital zircons in the overlying siliciclastic sedimentary successions illustrates the viability of these isotopic data to assess the degree of insularity of the Mojave province from Mesoproterozoic to Paleozoic time. The Mesoproterozoic Pinto Mountain Group was probably derived entirely from a relatively chronologically and isotopically homogeneous provenance within Mojave province basement. In contrast, the Neoproterozoic (i.e., postaccretion) Big Bear Group had a much more diverse provenance, and we suggest two hypothetical sources based on two paleocurrent scenarios. A source for Big Bear Group siliciclastic sediments may be found in a Hudsonian arc overprinted by Grenville orogenesis in eastern Laurentia, but this hypothesis fails to explain the lack of Archean and 1.7 Ga detrital zircons in these quartzites. Alternatively, a hypothesized western Rodinian source within the conjugate rift pair may represent a discrete buried subprovince of the Mojave province. This hypothesized western subprovince would reflect the late Archean and earlier Paleoproterozoic heritage of the Mojave province, would not have been greatly affected by ca. 1.7 Ga magmatism, but would have been intruded by ca. 1.45 Ga granites and overprinted by Grenville orogenesis. Detrital zircons in the overlying miogeoclinal Wood Canyon Formation and Zabriskie Quartzite were probably not derived from local Proterozoic crust of the Mojave province, based on their Hf isotopic signatures, but may have had a provenance in the 1.5–1.3 Ga southeastern Granite-Rhyolite province and its older basement that shifted toward a more continental interior provenance with more abundant Archean input by Cambrian time.

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