Reexamination of the Crustal Boundary Context of Mesoproterozoic Granites in Southern Nevada Using U-Pb Zircon Chronology and Nd and Pb Isotopic Compositions

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ABSTRACT

Granites crystallize from melts with a range of compositions and textures that provide important clues about the evolution of the continental crust. Rapakivi or A-type granites are usually inferred to be unrelated to active tectonic processes. Granites that fall into this category are widespread across the interior of North America. They are generally considered to be 1450–1400 Ma and anorogenic. We report new and substantially older U-Pb zircon ages of 1683.2 ± 4.7, 1681.4 ± 5.1, and 1683.3 ± 6.1 Ma for rapakivi granites from the Davis Dam area, the Lucy Gray Range, and the Newberry Mountains of southern Nevada, respectively. These granites are thus associated with the Ivanpah orogeny. Rapakivi granites from Gold Butte, Nevada, also previously thought to be 1450–1400 Ma, yielded a younger U-Pb zircon age of 1373 ± 23 Ma. In addition to these new age constraints, new Nd and Pb isotope data allow us to refine previously mapped isotopic crustal boundaries. Nd and Pb isotopes from the ~1680 Ma granites indicate a brief residence in the crust prior to crystallization, whereas the source of the younger Gold Butte granite appears to have significant crustal heritage. The modified isotopic province boundaries are now more consistent with each other than in earlier interpretations, a result that reinforces the view that these boundaries reflect fundamental tectonic features related to Paleoproterozoic crustal accretion. Our data imply that the spatial distribution of the classic anorogenic granite suite in North America is more restricted than previously thought. They also draw attention to the need for more extensive dating and radiogenic isotope measurements to probe the midcontinent belt of granites more broadly. Although plutons look alike, it can no longer be assumed that they were intruded synchronously or formed from the same source.

Online enhancements: supplementary tables and figures.

Introduction

Granites crystallize from melts with a range of compositions and textures that inform our understanding of the evolution of continental crust (e.g., Clarke 1992). In the western United States, isotopic mapping of granites has been used extensively to identify the boundaries of crustal basement provinces. Kistler and Peterman (1973) used the initial $^{87}Sr/^{86}Sr$ ratio from Mesozoic and Cenozoic plutons in California and Nevada to trace the edge of the North American craton (approximated as the $^{87}Sr/^{86}Sr_{initial} = 0.706$ isopleth; thick black line on the left side of fig. 1). Within the North American craton, Bennett and DePaolo (1987) defined crustal provinces on the basis of the distribution of initial Nd isotope ratios (initial ε_{Nd}; DePaolo and Wasserburg 1976) and Nd model ages of crust-mantle differentiation (T_{DM}; DePaolo 1981). With this approach, they divided the western United States into three provinces, labeled 1, 2, and 3 and bounded by dotted lines in figure 1. Wooden and Miller (1990) and Wooden and DeWitt (1991) used

Manuscript received September 27, 2015; accepted December 22, 2015; electronically published May 6, 2016.
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[The Journal of Geology, 2016, volume 124, p. 313–329] © 2016 by The University of Chicago.
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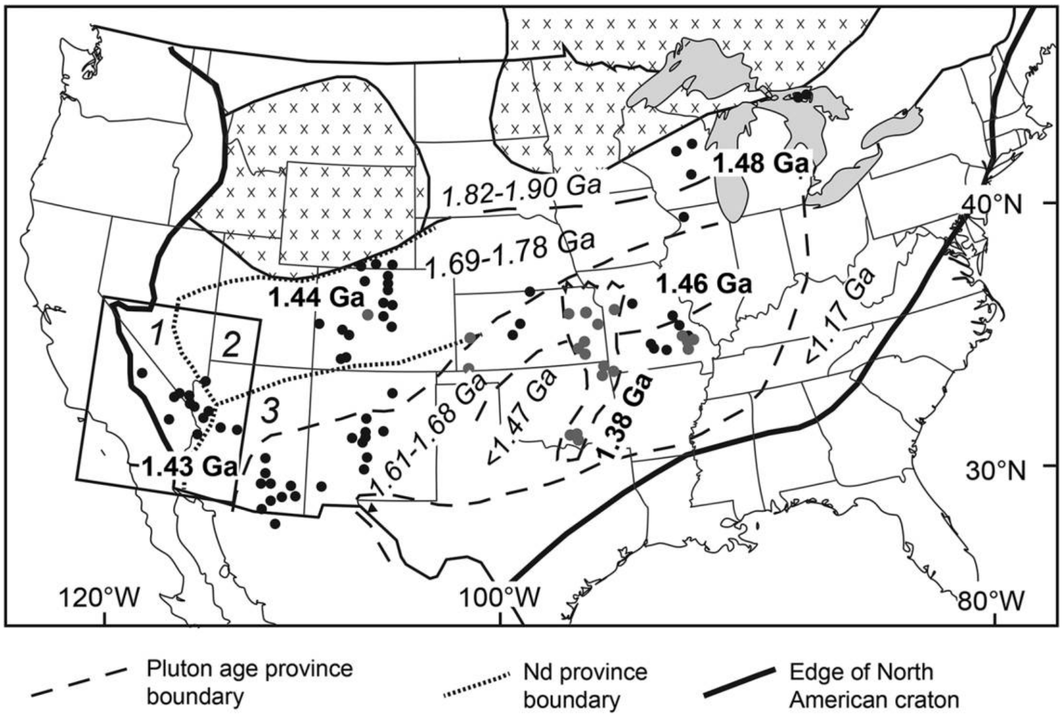

Figure 1. Map of the United States showing the distribution of anorogenic plutons: 1.34–1.41 Ga (gray dots) and 1.41–1.49 Ga (black dots). Average ages of plutons are shown in bold, and average ages of crustal province are shown in italics. The sources for the ages and descriptions of the plutons are from Anderson (1983). Bold lines represent the edge of autochthonous North America. In the western United States, the boundary of the North American craton is defined by the $^{87}Sr/^{86}Sr_{initial} = 0.706$ isopleth (Kistler and Peterman 1973). In the eastern United States, this boundary is defined by rocks associated with the Grenville orogeny. Dashed lines represent boundaries between age provinces. Areas with an X pattern represent Archean cratons (Anderson 1983). Dotted lines and italic numbers represent the Nd provinces of Bennett and DePaolo (1987). The box shows the location of figure 2. Gray areas represent the Great Lakes. Figure is modified from Anderson (1983).

whole-rock Pb isotopes to map crustal boundaries. They divided the region into the Mojave and Arizona provinces, which broadly agree with the provinces defined by Bennett and DePaolo (1987). Wooden and DeWitt (1991) also delineated a 75-km-wide boundary zone within which Pb isotope ratios show mixing relationships between the two provinces (shaded blue area in fig. 2*B*; Mojave and Arizona provinces are west and east of the transition zone, respectively). Their Arizona province is equivalent to the Yavapai province of other studies (e.g., Hoffman 1988; Karlstrom and Bowring 1988, 1993; Karlstrom and Humphreys 1998; Whitmeyer and Karlstrom 2007; Duebendorfer 2015). In this article, we use the term "Arizona province" when referring to the province defined by Nd and Pb isotopes and the term "Yavapai province" when referring to the tectonic evolution of Paleoproterozoic crustal blocks. Several studies (Duebendorfer et al. 2006; Duebendorfer 2015) have proposed that this transition zone represents the rifted leading edge of the Mojave block, developed in response to slab rollback in a subduction zone farther west, prior to the accretion of the Yavapai arc.

On the basis of regional variations in isotopic and geochronologic data, the following tectonic provinces have been proposed for the western United States (fig. 3): (1) the Archean Wyoming craton, which has protoliths and deformation ages between 3500 and 2500 Ma; (2) the Mojave province, which consists of pre–1800 Ma crustal material; (3) the Yavapai province, a 1760–1720 Ma juvenile arc terrane; and (4) the Mazatzal province, formed by 1700–1650 Ma supracrustal rocks on unknown basement (fig. 3; Hoffman 1988; Karlstrom and Bowring 1988, 1993; Karlstrom and Humphreys 1998; Whitmeyer and Karlstrom 2007). Bennett and DePaolo (1987) assigned a T_{DM} of 2300–2000 Ma to the Mojave province (their province 1) and 1800 Ma or younger to the Yavapai province (their province 3).

These terranes, known as the Transcontinental Proterozoic provinces, were amalgamated during the Proterozoic, between 1800 and 1600 Ma, through a process that involved accreting arcs to the stable Ar-

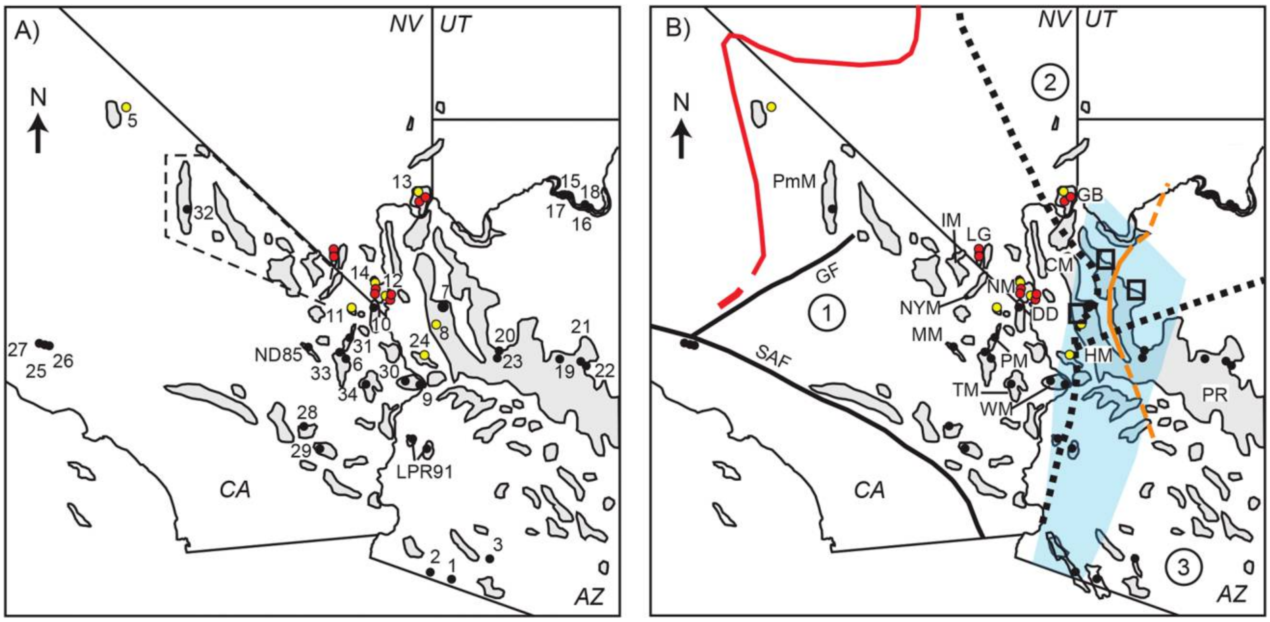

Figure 2. *A*, Map of the southwestern United States showing the locations of samples used in this study. Red dots represent samples analyzed as part of this study (data for these samples are reported in tables 1–4 and are not individually identified on this map). Yellow dots are samples from Bennett and DePaolo (1987) that have been reassigned to a different crustal province using newer available age data (this study; Chamberlain and Bowring 1990; Wooden and DeWitt 1991). Black dots are samples from Nelson and DePaolo (1985), identified as ND85, and from Lerch et al. (1991), identified as LPR91, as well as other samples from Bennett and DePaolo (1987) that have not been reassigned. The dashed polygon represents the area sampled by Ramo and Calzia (1998) around Death Valley. Numbers and abbreviations next to sample locations identify them in table S1. *B*, Map of the same area as *A* showing previously published isotopic boundaries. Black lines show major faults (GF = Garlock fault; SAF = San Andreas fault). The red line is the $^{87}Sr/^{86}Sr_{initial} = 0.706$ isopleth for Mesozoic and Cenozoic granites from Kistler and Peterman (1973), usually assumed to be the edge of autochthonous North America. The dotted lines are the proposed boundaries for crustal provinces within North America of Bennett and DePaolo (1987) based on Nd isotope measurements. Their proposed provinces are indicated by circled numbers 1, 2, and 3. The shaded blue area is the Pb isotopic boundary zone suggested by Wooden and DeWitt (1991). The orange line is the Pb crustal boundary proposed by Chamberlain and Bowring (1990), which coincides with the boundary proposed by Duebendorfer et al. (2006) on the basis of pseudogravity data. Open boxes indicate areas sampled by Chamberlain and Bowring (1990). Ranges: CM = Cerbat Mountains; DD = Davis Dam; DM = Dead Mountains; GB = Gold Butte; HM = Hualapai Mountains; IM = Ivanpah Mountains; LG = Lucy Gray Range; MM = Marble Mountains; NM = Newberry Mountains; NYM = New York Mountains; PmM = Panamint Mountains; PM = Piute Mountains; PR = Poachie Range; TM = Turtle Mountains; UG = Upper Granite Gorge; WM = Whipple Mountains. In both maps, shaded gray areas are outcrops of Proterozoic crystalline rocks. States (in italics): AZ = Arizona; CA = California; NV = Nevada; UT = Utah. Figure is modified from Karlstrom and Humphreys (1998).

chean craton of North America (the Wyoming province; Karlstrom and Houston 1984; Karlstrom and Bowring 1993). It is thought that they are separated by prominent thrust faults (fig. 3; Karlstrom and Humphreys 1998; Holland et al. 2015). However, the preserved outcrop of these proposed structural boundaries is spatially limited, and their regional configuration is therefore uncertain (fig. 3). Alternative hypotheses that emphasize transtensional tectonics between different crustal blocks have also been proposed (Bickford and Hill 2007). The assembly of the Transcontinental Proterozoic provinces was followed by a continent-wide magmatic event that involved the intrusion of A-type granites (Loiselle and Wones 1979), generally accepted to be 1450–1400 Ma (gray and black circles in fig. 1; Anderson 1983; Anderson and Bender 1989; Karlstrom and Humphreys 1998). These granites are usually called rapakivi, although they are not necessarily characterized by the distinctive petrographic rapakivi texture (Anderson and Bender 1989). They are considered anorogenic granites owing to the absence or weak development of deformational fabric (although some have well-developed emplacement-related fabrics) and the apparent lack of temporal association to any local orogenic events. Rapakivi granite, first recognized in

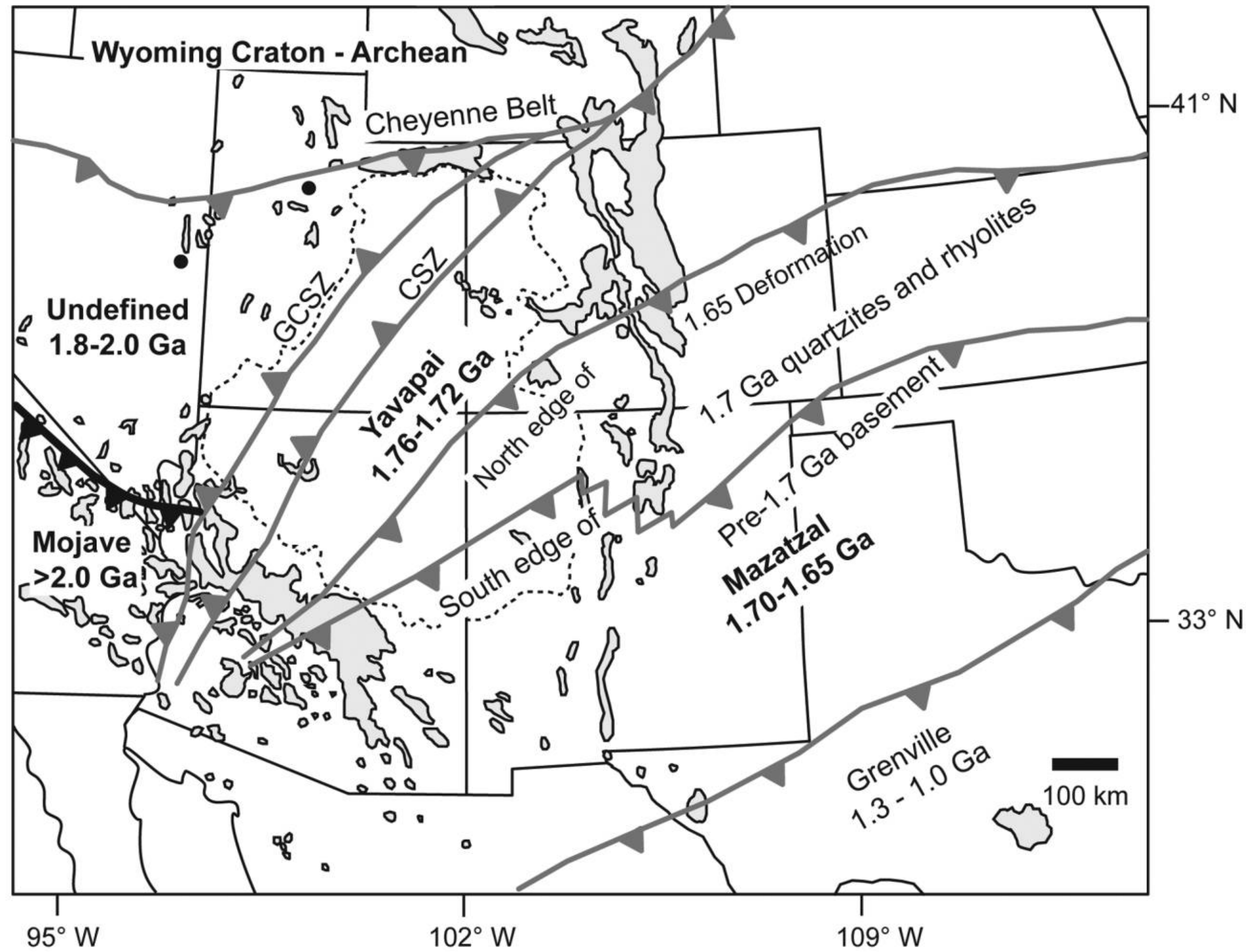

Figure 3. Map showing the location and ages of the various tectonic belts amalgamated during the Paleoproterozoic in the southwestern United States. Lines with teeth are sutures with teeth on the upper plate. Gray lines are from Karlstrom and Humphreys (1998). The bold black line represents the new northern boundary of the Mojave microplate proposed in this study. This boundary does not correspond to any particular structure in the field, and the teeth on the line suggest the direction of subduction based on the location of the arc. Black dots represent sample locations used in Farmer and DePaolo (1984; table S1). The dashed line represents the outline of the Colorado Plateau. Shaded gray areas are outcrops of Proterozoic rocks. Outcrops in central Nevada and Utah are primarily Neoproterozoic sedimentary rocks. Figure is modified from Karlstrom and Humphreys (1998), Condie (1992), and Holland et al. (2015). CSZ = Crystal shear zone; GCSZ = Gneiss Canyon shear zone.

Finland (Anderson 1983), is a special variant of A-type granite, with large, zoned feldspar phenocrysts. Rapakivi granites are argued by some to have been produced by partial melting of the crust in the vicinity of mantle melts and by others to have been derived exclusively from previously depleted crustal sources (Creaser et al. 1991). In North America, a belt of granites, considered to be A-type, extends for 3,500 km from Labrador to southern California (Anderson 1983; Anderson and Bender 1989) and has long been thought to represent the stabilization of the North American continent at 1450–1400 Ma (Silver 1978; Anderson 1983).

Recent studies have refined the timing of orogenic and basin-forming events recorded by Proterozoic rocks of the southwestern United States (e.g., Jessup et al. 2006; Jones et al. 2010, 2011; Doe et al. 2012; Daniel et al. 2013), highlighting a more complex tectonic evolution than the first-order scheme reviewed above, especially during the anorogenic period of plutonism. The more recent studies suggest an interval of clastic deposition at ~1450 Ma, coeval with or closely followed by a span of metamorphism and ductile deformation and consistent with the existence of a long-lived active accretionary margin (Jessup et al. 2006; Jones et al. 2010, 2011; Doe et al. 2012; Daniel et al. 2013). Most previous studies have focused on the Proterozoic rocks of Arizona, New Mexico, and Colorado. The work presented here investigates an area of southern Nevada that includes several of the inferred crustal boundaries. New geochronologic and isotopic data allow us to refine the boundaries of crustal provinces and the timing of supposed 1450–1400 Ma plutonism. These data shed new light on the Proterozoic development of the North American craton.

Sample Localities

We collected granites with rapakivi texture (i.e., alkali feldspar mantled by plagioclase) from Gold Butte, Davis Dam, the Newberry Mountains, and the Beer Bottle Pass area of Lucy Gray Range (GB, DD, NM, and LG, respectively, in fig. 2). The sampled plutons are metaluminous granites, inferred to be intruded into the upper crust at depths of 8–17 km and at temperatures of up to 790°C (Anderson 1983). The rocks are mostly undeformed, but they display foliation close to their boundaries that we interpret as being associated with emplacement. The Beer Bottle Pass granite is an exception. Mylonitic shear zones in this body are up to 100 m thick (Duebendorfer and Christiansen 1995). In general, samples were taken from where there was the least evidence for deformation. Sample locations are listed in table 1.

Analytical Methods

Neodymium and Lead Isotope Compositions. Nd isotopes were measured on homogenized whole-rock samples, while Pb isotopes were measured in feldspar crystals that were taken from crushed aliquots of the same samples. About 500 g of pristine rock chips were pulverized using a shatter box with a tungsten carbide vessel. Approximately 200 mg of pulverized whole rock and 100 mg of feldspar crystals were dissolved for Nd and Pb analyses, respectively. Afterward, all chemical procedures were carried out in a class 1000 ultraclean laboratory at Lamont-Doherty Earth Observatory (LDEO). Pb and Nd were extracted from dissolved sample solutions via ion chromatography using Biorad AG1-X8 and Eichrom Tru-Spec/Ln-Spec resin, respectively. Isotope ratios were measured in static mode with standard sample bracketing and Tl doping techniques using a Thermo-Fisher Neptune multicollector inductively coupled plasma mass spectrometer (MC-ICP-MS) at LDEO. A subset of Pb analyses was done on a VG-Axiom MC-ICP-MS at LDEO using the same method. The complete analytical procedure is described in Cai et al. (2015).

$^{143}Nd/^{144}Nd$ ratios were corrected for mass fractionation using $^{146}Nd/^{144}Nd = 0.7219$. The JNdi-1 standard was measured between every sample to monitor instrument drift. The average measured $^{143}Nd/^{144}Nd$ value of JNdi-1 was 0.512085 ± 6 (2σ; $n = 18$). Unknowns were normalized to a JNdi-1 value of 0.512115 (Tanaka et al. 2000). Two aliquots of La Jolla standard measured to check data accuracy yielded $^{143}Nd/^{144}Nd$ of 0.511863 and 0.511860, which agree well with the reported value of 0.511858 ± 7 (Tanaka et al. 2000).

Pb isotopes were corrected for mass fractionation by adding Tl to standards and samples and normalizing measured $^{203}Tl/^{205}Tl$ values to $^{203}Tl/^{205}Tl = 0.41844$ (Thirlwall 2002). National Institute of Standards SRM 981 standards were run before and after each sample to monitor instrument drift. Unknowns were normalized to an SRM 981 value of $^{206}Pb/^{204}Pb =$

Table 1. Sample Locations

Sample	Locality	Coordinates: Easting	Coordinates: Northing	UTM zone	Lithology
13	Newberry Mountains	697429	3895197	11	Rapakivi granite
17	Newberry Mountains	702038	3900084	11	Rapakivi granite
29	Newberry Mountains	705873	3909916	11	Rapakivi granite
35	Lucy Gray Range	654464	3949321	11	Rapakivi granite
39	Lucy Gray Range	657636	3941407	11	Rapakivi granite
20	Davis Dam	723202	3898520	11	Rapakivi granite
22	Davis Dam	718892	3899007	11	Rapakivi granite
L	Gold Butte	752561	4014489	11	Rapakivi granite
W	Gold Butte	756695	4011327	11	Rapakivi granite
RA09-10	Panamint Range	490854	3987641	12	Felsic granite
RA09-12	Panamint Range	490764	3987611	12	Felsic granite

Note. UTM = Universal Transverse Mercator.

16.9356, $^{207}Pb/^{204}Pb$ = 15.4891, and $^{208}Pb/^{204}Pb$ = 36.7006 (Todt et al. 1996). BCR-2 standards were routinely analyzed to monitor data accuracy, and the results agree well with published values (Jweda et al. 2016). Additional analytical metadata are provided in the supplementary tables (available online).

U-Pb Zircon Geochronology. Zircons were separated from the samples using standard techniques, including a Wilfley shaking table and magnetic and heavy liquid separations (lithium polytungstates and methylene iodide). Zircons from a subsample of each separate were mounted on 1-inch epoxy discs and polished to expose the interior of the grains. U-Pb dating of zircons was undertaken by laser ablation ICP-MS at the Arizona LaserChron Center. The analyses involve ablation of zircon with a Photon Machines Analyte G2 excimer laser using a spot diameter of 30 μm (for very small grains, a spot diameter of 20 μm was used). Analytical details are described in Gehrels et al. (2008). The resulting ages with fully propagated errors were calculated using ISOPLOT (Ludwig 2008).

Results

U-Pb Zircon Ages. Rather than the expected ages of 1450–1400 Ma, U-Pb zircon ages of the rapakivi granites fall into two distinct groups (table 2). The older group (group 1 in this article) includes samples from Davis Dam, the Lucy Gray Range, and the Newberry Mountains, with ages of 1683.2 ± 4.7, 1681.4 ± 5.1, and 1683.3 ± 6.1 Ma, respectively. The average for these samples is 1682.6 ± 3.2 Ma. The granite from Gold Butte (group 2) yields a younger age of 1374.5 ± 23 Ma.

Nd Isotopes. Nd isotope and T_{DM} values of these granites also cluster into two broad groups, consistent with those defined by U-Pb zircon ages (fig. 4; table 3). The ~1680 Ma granites from group 1 have a T_{DM} of ~1860 Ma and initial ε_{Nd} values between +0.62 and +1.47, consistent with derivation from a slightly depleted mantle or from sources with a very brief prior crustal residence (DePaolo 1988). The Gold Butte granite has a T_{DM} of ~1760 Ma and initial ε_{Nd} values of −0.9 to −1.3, data that indicate protracted residence in the crust prior to formation of the granite. Figure 5 shows a plot of $^{147}Sm/^{144}Nd$ versus ϵ_{Nd} today for our samples as well as data from previous studies for reference (table S1).

Pb Isotopes. The measured $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ values for the feldspars are reported in table 4. $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ values are plotted with data from previous studies (table S2) in figure 6*A* and with the two-stage evolution curve of Stacey and Kramers (1975) in figure 6*B*. Feldspars have very low initial U/Pb ratios; therefore, measured Pb isotopic compositions closely represent those of the magma at the time of the last isotopic equilibration (e.g., Hemming et al. 1996). The small amount of U that is trapped in the mineral produces a small amount of radiogenic Pb and results in populations that form linear arrays (Tyrrell et al. 2012). Thus, feldspar Pb isotopic compositions can be used to differentiate crustal domains (e.g., Chamberlain and Bowring 1990). Both group 1 and group 2 (Gold Butte) closely follow the 1700 Ma reference isochron proposed for the Mojave terrane. Two analyses of Panamint Range granites (RA09-10, RA09-12; table 4) show even more radiogenic $^{207}Pb/^{204}Pb$ ratios, possibly as a result of greater involvement of Archean crustal material in that area. To emphasize variations in regional $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ isotope compositions, we adopt the normalization technique proposed by Wooden and DeWitt (1991). They defined

Table 2. U-Pb Zircon Ages

Sample[a]	Locality	n	Average age (Ma)[b]	MSWD[c]	Total error (Ma)[d]
13	Newberry Mountains	18	1685.0	.7	8.0
17	Newberry Mountains	17	1683.7	.4	11.5
29	Newberry Mountains	17	1681.1	.2	11.9
35	Lucy Gray Range	17	1682.3	.64	10.2
39 (1)	Lucy Gray Range	12	1681.6	3.9	7.9
39 (2)	Lucy Gray Range	27	1680.4	1.12	8.3
20	Davis Dam	24	1683.0	1.1	4.7
22	Davis Dam	18	1683.3	.6	8.1
L	Gold Butte	18	1372.5	.3	42.1
W	Gold Butte	12	1376.4	.25	18.4

[a] All Universal Transverse Mercator locations are given in table 1.
[b] Ages are the weighted mean (weighting according to the square of the internal uncertainties) of measurements taken on n zircons per sample.
[c] Mean square weighted deviation of each data set.
[d] Total error of the age is determined by quadratic addition of the systematic (or internal) errors and the random (or external) uncertainties. These errors represent the 95% confidence level.

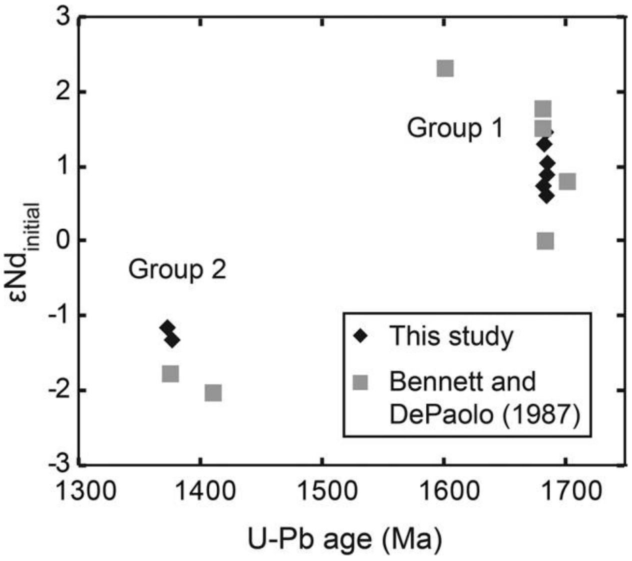

Figure 4. Plot showing the correlation between initial εNd values and U-Pb ages for granite samples measured by Bennett and DePaolo (1987; table S1) and this study (tables 2, 3). Note that all of the samples with positive initial εNd values cluster close to 1700 Ma.

a variable called Δ_{Jerome}, which is expressed as 100 times the difference between the measured $^{207}Pb/^{204}Pb$ and a modeled $^{207}Pb/^{204}Pb$ value that is calculated on the basis of the measured value of $^{206}Pb/^{204}Pb$ and the 1700 Ma isochron that passes through the Pb isotopic values of galenas from a mine in Jerome, Arizona ($^{206}Pb/^{204}Pb = 15.725$, $^{207}Pb/^{204}Pb = 15.270$, and $^{208}Pb/^{204}Pb = 35.344$). We report these values in table 4.

Discussion

Our data show that granites that have long been considered a part of the extensive 1450–1400 Ma anorogenic plutonic suite in the southwestern United States instead belong to two distinct episodes of plutonism, one at ~1680 Ma and another at ~1370 Ma. Within our samples, there is no evidence for plutonism during the interval of 1450–1400 Ma. Our data suggest that the Nd isotope boundaries defined by Bennett and DePaolo (1987) should be adjusted, with the new boundary location showing a striking coincidence with the Pb isotope boundaries proposed by Chamberlain and Bowring (1990) on the basis of feldspar composition and by Wooden and DeWitt (1991) on the basis of whole-rock data.

The crustal province(s) of our samples can be determined using the criteria established in these earlier studies. Wooden and DeWitt (1991) defined the Mojave province as having $\Delta_{\mathrm{Jerome}} > 6$, with higher $^{207}Pb/^{204}Pb$ ratios with respect to samples from the Arizona province at a given $^{206}Pb/^{204}Pb$ ratio (fig. 6*A*). This was attributed to older crustal material involved in the formation of the Mojave province (Wooden et al. 1988). All of the feldspars in our data set satisfy this condition (table 4), consistent with Mojave province affinity. Figure 6*B* shows that the samples from our study form a steeper trend than the 1700 Ma Mojave isochron (for reference, an errorchron generated with these data represents an age of 1850 Ma), suggesting an older inherited age, consistent with this interpretation. Using Nd isotopes, Bennett and DePaolo (1987) defined province 1 (their equivalent of the Mojave province) as containing rocks with $T_{\mathrm{DM}} >$ 2000 Ma and initial $\varepsilon_{\mathrm{Nd}}$ between -2 and -4. These characteristics, however, are not found in any of our samples (table 3). Bennett and DePaolo defined province 2 as having $T_{\mathrm{DM}} = 2000$–1800 Ma and province 3 (their equivalent of the Arizona province) as $T_{\mathrm{DM}} =$ 1800–1700 Ma. On the basis of these criteria, group 1 of our samples should be part of province 2, and group 2 should be part of province 3.

Crustal Affinity. Our data document two distinct episodes of plutonism in southern Nevada. One episode occurred at ~1680 Ma and is represented by group 1 granites, from the Lucy Gray Range, the Newberry Mountains, and Davis Dam (LG, NM, and DD in fig. 2*B*), as well as by granites from the Cerbat and Hualapai Mountains (CM and HM in fig. 2*B*; Chamberlain and Bowring 1990; Duebendorfer et al. 2001) and the New York and Ivanpah Mountains (NYM and IM in fig. 2*B*; Wooden and Miller 1990), east and west of our study area, respectively. The gneisses exposed in the New York and Ivanpah Ranges were metamorphosed and deformed at 1740–1680 Ma (Wooden and Miller 1990; Strickland et al. 2013). The undeformed ~1680 Ma plutons are interpreted to mark the end of the Ivanpah orogeny (Wooden and Miller 1990; Strickland et al. 2013). The Cerbat Mountains also show evidence of metamorphism and deformation between 1740 and 1680 Ma (Duebendorfer et al. 2001). Undeformed granites, dated at ~1680 Ma, have been described in these ranges (Chamberlain and Bowring 1990; Duebendorfer et al. 2001). The Ivanpah orogeny is coeval with, and considered by Karlstrom and Humphreys (1998) and Whitmeyer and Karlstrom (2007) to be part of, the larger Yavapai orogeny.

Group 1 granites yield positive initial $\varepsilon_{\mathrm{Nd}}$ values (+0.62 to +1.47) and U-Pb zircon ages of 1682.3 ± 2.6 Ma. These features suggest that they likely represent juvenile arc crust. These granites yield an average T_{DM} of 1900 ± 40 Ma, which could indicate ~200 m.yr. of crustal residence of the protolith of

Table 3. Sm and Nd Results

Sample[a]	Locality	Nd[b] (ppm)	Sm[b] (ppm)	$^{143}Nd/^{144}Nd$[b]	$^{147}Sm/^{144}Nd$[c]	Age[d] (Ma)	εNd[e] now	$^{143}Nd/^{144}Nd$[f] initial	$^{143}Nd/^{144}Nd$ CHUR(t)	εNd[f] initial	T_{CHUR}[g] (Ma)	T_{DM}[g] (Ma)
17	Newberry Mountains	73.84	12.98	.511685	.106	1683.7	−18.58	.510514	.510460	1.06	1593.8	1868.2
29	Newberry Mountains	88.14	16.43	.511771	.112	1681.1	−16.91	.510530	.510463	1.31	1561.1	1859.1
35	Lucy Gray Range	70.48	13.61	.511823	.116	1682.3	−15.90	.510537	.510462	1.47	1541.0	1855.1
39	Lucy Gray Range	90.90	15.74	.511655	.104	1680.4	−19.18	.510503	.510464	.75	1617.6	1883.2
20	Davis Dam	41.67	5.97	.511447	.086	1683.0	−23.23	.510493	.510461	.62	1639.5	1865.9
22	Davis Dam	74.16	11.72	.511560	.095	1683.3	−21.02	.510507	.510461	.90	1614.7	1861.9
L	Gold Butte	131.70	22.39	.511728	.102	1372.5	−17.74	.510806	.510864	−1.15	1466.7	1760.2
W	Gold Butte	111.37	17.51	.511648	.095	1376.4	−19.31	.510792	.510859	−1.31	1476.0	1750.0

[a] All Universal Transverse Mercator locations are given in table 1.
[b] Measured values.
[c] $^{147}Sm/^{144}Nd = [Sm\ (ppm)/Nd\ (ppm)] \times 0.602$.
[d] U-Pb zircon ages obtained in this study.
[e] εNd was calculated following DePaolo and Wasserburg (1976) using CHUR $^{143}Nd/^{144}Nd = 0.512638$.
[f] The initial $^{143}Nd/^{144}Nd$ and εNd values were calculated using the U-Pb zircon crystallization ages of each sample obtained as part of this study and $\lambda_{Sm} = 6.54 \times 10^{-12}\ yr^{-1}$.
[g] T_{DM} (depleted mantle model age) and T_{CHUR} (CHUR model age) are calculated following DePaolo (1981).

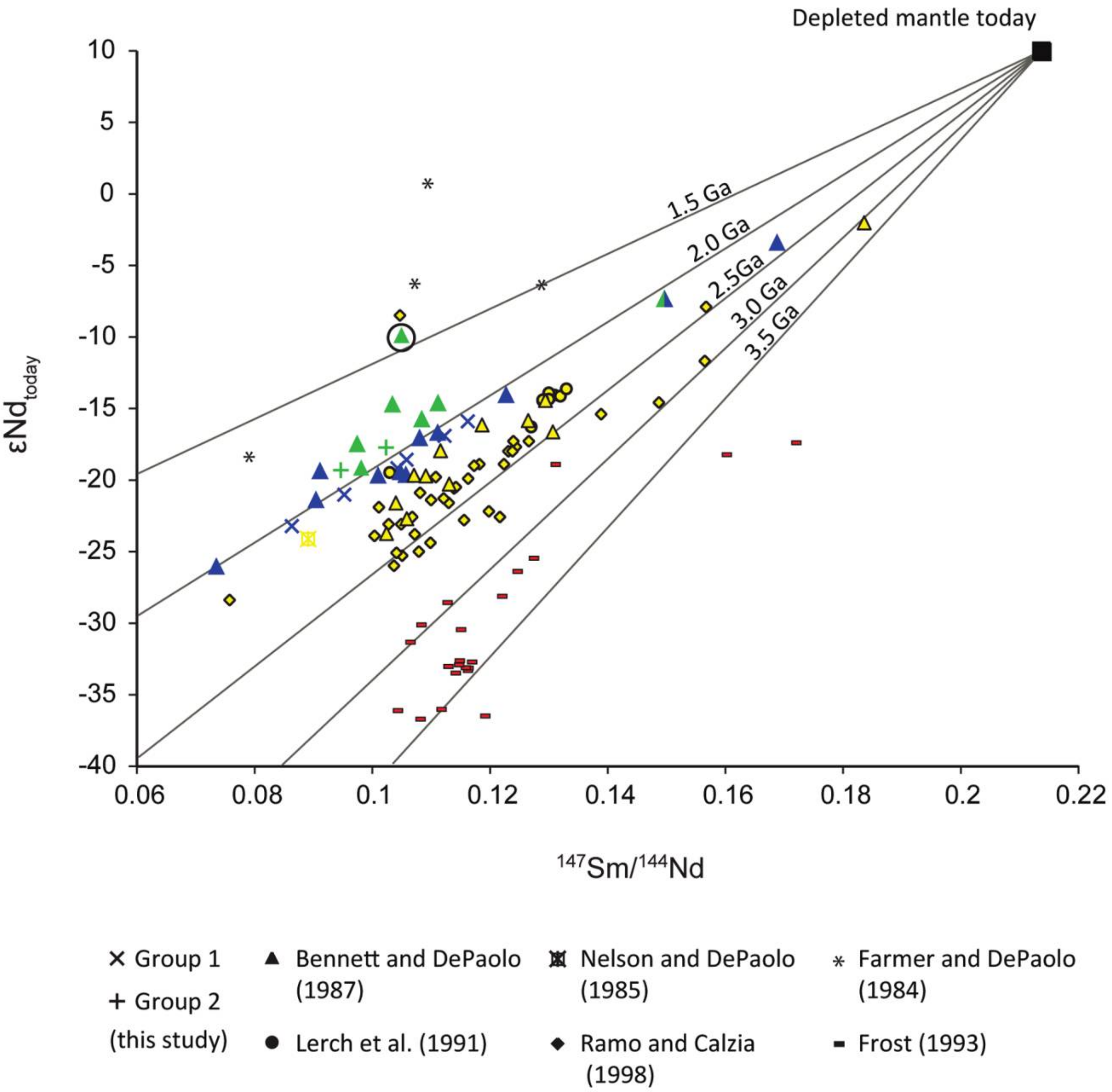

Figure 5. Plot of $^{147}Sm/^{144}Nd$ versus εNd showing data from this and other studies. Colors show province affinity: red symbols represent the Wyoming province (data from Frost 1993), yellow symbols represent the Mojave province, blue symbols represent the transition area proposed in this study that is north of the Mojave, and green symbols represent province 3 of Bennett and DePaolo (1987; shown in fig. 1 and equivalent to the Arizona province of Wooden and DeWitt 1991). The circled green triangle represents the anomalous sample from the Dead Mountains, California. The half-green/half-blue triangle represents the sample from Bagdad, Arizona (Bennett and DePaolo samples 10 and 23, respectively, in table S1). The provinces more or less follow trends that correspond to their respective model ages (illustrated as model isoage lines that radiate from modern depleted mantle). The black square corresponds to modern depleted mantle ($\varepsilon Nd = 10$ and $^{147}Sm/^{144}Nd = 0.2137$; White 2014). Model isoage lines are calculated using 6.54×10^{-12} as the decay constant for ^{147}Sm (Lugmair and Marti 1978).

the plutons prior to zircon crystallization. Paragneisses from the Ivanpah Mountains (IM in fig. 2*B*) have detrital zircon age populations of 2150–1800 Ma and metamorphic zircon ages of 1760–1670 Ma (Strickland et al. 2013), consistent with this inferred history.

Group 2 granites from Gold Butte record a younger episode of plutonism at ~1370 Ma. Gold Butte

Table 4. Pb Results

Sample[a]	Locality	$^{206}Pb/^{204}Pb$ [b]	$^{207}Pb/^{204}Pb$[b]	$^{206}Pb/^{204}Pb$[b]	Δ_{Jerome}[c]
17	Newberry Mountains	16.4909	15.4280	36.1333	7.77
29	Newberry Mountains	16.1455	15.3893	35.6393	7.49
17	Newberry Mountains	16.1029	15.3876	35.6387	7.77
35	Lucy Gray Range	16.1506	15.3870	35.7249	7.21
39	Lucy Gray Range	16.2620	15.4027	35.8873	7.62
20	Davis Dam	16.2905	15.4103	36.6798	8.08
22	Davis Dam	16.3830	15.4185	35.7644	7.94
L	Gold Butte	16.4391	15.4273	35.5917	8.24
W	Gold Butte	16.2373	15.3974	35.9092	7.35
L	Gold Butte	16.2488	15.4028	35.8606	7.77
N	Gold Butte	16.1855	15.3931	35.8420	7.46
Q	Gold Butte	16.1448	15.3891	35.8337	7.48
RA09-10	Panamint Range	17.7681	15.6406	39.1589	15.72
RA09-12	Panamint Range	19.7247	15.8637	42.4674	17.64

[a] Samples in bold were analyzed using an Axiom multicollector inductively coupled plasma mass spectrometer. All Universal Transverse Mercator locations are given in table 1. Reported values are averages of several runs. Individual runs can be found in table S5.
[b] Measured value.
[c] Calculated following Wooden and DeWitt 1991.

granite yields a T_{DM} of 1780 $\pm$ 20 Ma, which is younger than those of group 1, but with a more negative initial ε_{Nd} (-0.9 to -1.3) that reflects significant assimilation of older crustal material (DePaolo 1988). Metamorphism also appears to have occurred later at Gold Butte than in the Ivanpah Mountains. One sample from the Gold Butte gneiss yielded a U-Pb zircon age of 1670 Ma (no error reported; Karlstrom et al. 2010). Zircons obtained from a Cretaceous two-mica granite located at Gold Butte (Brady et al. 2000; Karlstrom et al. 2010) yielded a U-Pb age of 1679.7 $\pm$ 14.8 Ma (Almeida 2014), consistent with inheritance from the gneissic protolith. These ages imply that the gneisses of Gold Butte formed later than those of the Ivanpah, New York, and Cerbat Mountains.

Nd Province Boundaries in the Southwestern United States. As initial ε_{Nd} values depend on both Sm/Nd ratios and adequate age control, they may not be as reliable in crustal province designations as T_{DM} values. Bennett and DePaolo (1987) defined Nd isotope provinces on the basis of T_{DM} and initial εNd values (fig. 1). Their proposed junction of provinces 1, 2, and 3 is located in the Nevada-Arizona-California tristate area (fig. 2B). In some cases, if the T_{DM} was not in the designated range, Bennett and DePaolo (1987) used the isotopic evolution path to assign samples to each province. For example, samples from the Dead and Homer Mountains have T_{DM}'s of 1280 and 1890 Ma, respectively, but on the basis of their isotopic evolution path they were included in province 1, defined as T_{DM} = 2300–2000 Ma. However, the crystallization ages assumed in Bennett and DePaolo (1987) were incorrect in many cases, leading to erroneous initial ε_{Nd} values (although the calculated T_{DM} remains unchanged). Using more recent U-Pb zircon ages from the Hualapai Mountains, the Lucy Gray Range, the Newberry Mountains, and Gold Butte (this study; Chamberlain and Bowring 1990; Wooden and DeWitt 1991) as well as new Nd isotope data from this study, we reevaluate the locations of their province boundaries in the southwestern United States. We propose a new set of province boundaries using T_{DM} as the main criterion (purple lines in fig. 7). Our boundaries are consistent with most available Nd isotopic data. There are two samples from Bennett and DePaolo (1987) that do not agree with our boundaries. One is from the Dead Mountains (DM in fig. 2; circled green triangle in fig. 5). This sample is enigmatic, as its T_{DM} (1280 Ma) is younger than the assumed crystallization age. The second is a sample from the Poachie Range (PR in fig. 2), which is also a complex area on the edge of the Pb boundary zone (discussed further below). We show corrected initial ε_{Nd} values in table S1, recalculated using U-Pb zircon ages. In northwestern Arizona, the new Nd boundary is well aligned with the Pb isotope boundary suggested by Chamberlain and Bowring (1990), on the western limit of the Pb boundary zone of Wooden and DeWitt (1991; orange line and shaded blue area, respectively, in figs. 2*B* and 7*B*). This Pb boundary zone is extended to the Upper Granite Gorge in the Grand Canyon (fig. 2) on the basis of Pb isotope values measured by Hawkins et al. (1996) that show a transition of Δ_{Jerome} values from Mojave type to Arizona type (table S2).

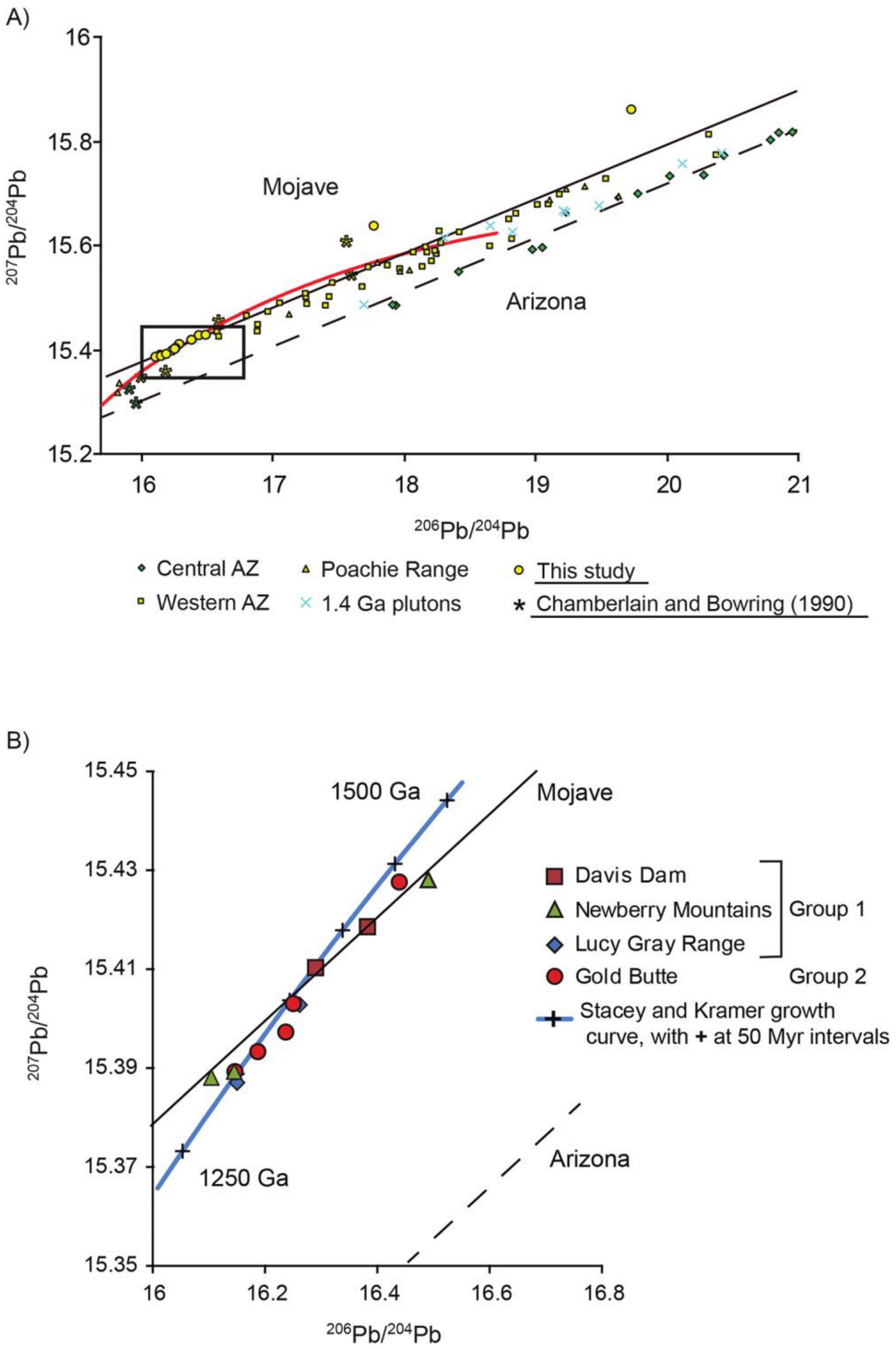

Figure 6. *A*, Plot of ^{206}Pb/^{204}Pb versus ^{207}Pb/^{204}Pb for samples from Wooden and DeWitt (1991), Chamberlain and Bowring (1990), and this study. Measurements from central Arizona, western Arizona, the Poachie Range, and 1.4 Ga plutons were done on whole-rock samples by Wooden and DeWitt (1991). Measurements from Chamberlain and Bowring (1990) and this study were done on feldspars (underlined in legend). Samples are colored by province, as defined by Wooden and DeWitt (1991): yellow for the Mojave province, green for the Arizona province, and blue for the Pb boundary zone. The black lines are the 1.7 Ga reference isochrons defined by Wooden and DeWitt (1991) for the Arizona and Mojave provinces. The higher ^{207}Pb/^{204}Pb values suggest higher initial U/Pb and correspond to the Mojave trend. The red line is the Stacey and Kramers (1975) two-stage common Pb evolution line. AZ = Arizona. *B*, Plot of ^{206}Pb/^{204} Pb versus ^{207}Pb/^{204}Pb for the area highlighted in the black box in *A*. The blue line represents the two-stage evolution line of Stacey and Kramers (1975) plotted between 1100 and 1700 Ma with a plus symbol placed at 50-m.yr. intervals along the curve. Only samples from this study are shown. Analytical errors are approximately half the size of the symbol used. All of the studied samples are clearly part of the Mojave trend. However, the samples form a steeper trend than the 1.7 Ga reference isochrons, implying older heritage.

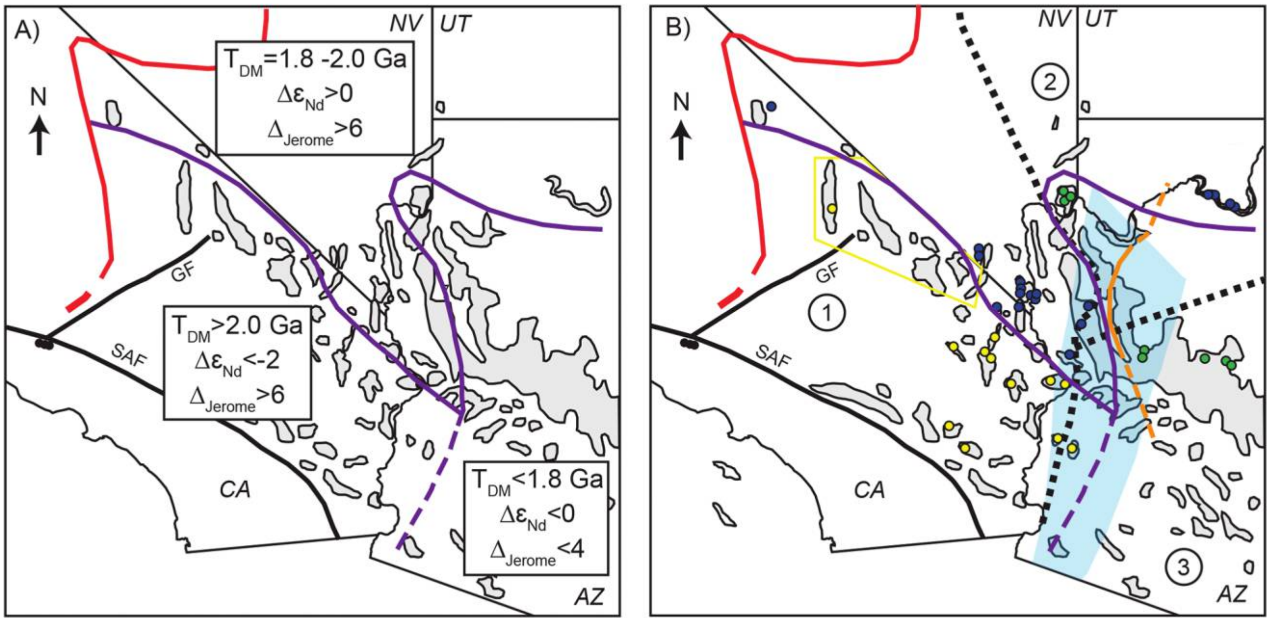

Figure 7. *A*, Map of figure 2 showing the crustal boundaries proposed in this study (marked as purple lines), based on Nd and Pb isotopic characteristics. For reference, the red line is the $^{87}Sr/^{86}Sr_{initial}$ = 0.706 isopleth from Kistler and Peterman (1973), usually assumed to be the edge of autochthonous North America. *B*, Map of the southwestern United States showing the main isotopic boundaries inferred from this study (marked as purple lines) and previous studies. Dotted lines represent boundaries for crustal provinces proposed by Bennett and DePaolo (1987) based on Nd isotope measurements. Their proposed province numbers are circled. The shaded blue area represents the Pb isotope province boundary zone suggested by Wooden and DeWitt (1991), and the orange line represents the Pb crustal boundary proposed by Chamberlain and Bowring (1990). Samples are color coded as in figure 5 (yellow = Mojave; green = Arizona; blue = transition area). The yellow outline corresponds to samples from Ramo and Calzia (1998), all of which correspond to the Mojave province. Faults: GF = Garlock fault; SAF = San Andreas fault. In both maps, shaded gray areas are outcrops of Proterozoic crystalline rocks. States (in italics): AZ = Arizona; CA = California; NV = Nevada; UT = Utah. Figure is modified from Karlstrom and Humphreys (1998).

Two intriguing new insights emerge from our data. First, the geometry of the boundary lines defined by Nd and Pb isotopes resembles that of the $^{87}Sr/^{86}Sr$ = 0.706 isopleth (red line in fig. 2*B*), which is considered the edge of Proterozoic North American continental lithosphere (Kistler and Peterman 1973). The Pb and Nd boundaries that we propose here are located to the east of this feature. The configuration of the Pb boundary is simpler than that of the Nd boundaries. The present locations of these isotopically defined features were affected by regional crustal shortening and extension during the Mesozoic and Cenozoic, respectively. Deformation would have been distributed in a nonuniform manner, thus altering the spatial relationship between these lines. However, the difference in complexity between the Pb and Nd lines prior to the deformation would be preserved. Moreover, the observation that Pb isotopes for some samples indicate province 1 (Mojave) affinity whereas Nd isotopes indicate province 3 (Arizona) affinity suggests that the extent of mixing in the Pb and Nd systems may have varied geographically. Examples of this are Gold Butte, which has Δ_{Jerome} = 7.35–8.24 but T_{DM} = 1750 Ma and initial ε_{Nd} = −0.5 to −1, and the Bennett and DePaolo (1987) samples from Bagdad, Arizona (samples 20 and 23 in table S1). These samples lie within the Pb boundary zone of Wooden and DeWitt (1991) in an area with Δ_{Jerome} between 4 and 8. One of the samples, however, has Nd isotopic characteristics that places it in province 3 (Arizona; T_{DM} = 1750 Ma and initial ε_{Nd} = 4.02), and a second sample has a T_{DM} that corresponds to province 2.

The Gneiss Canyon and Crystal shear zones (GCSZ and CSZ in fig. 3), both exposed in the Grand Canyon, have been interpreted as the Mojave-Yavapai crustal boundary in western Arizona (Wooden and DeWitt 1991; Karlstrom and Humphreys 1998; Holland et al. 2015). However, despite excellent exposure and subvertical orientation in the canyon itself, confidence in tracing this boundary to the north and south is limited by the lack of additional outcrops. The orientation of the Pb boundary zone has been used to further constrain the regional trend of the Mojave-Yavapai boundary, resulting in a relatively simple geometry. No such shear zones have been mapped in southern Nevada. Province boundaries in that area are therefore defined only on the basis of Nd isotope data, resulting in a more complex geometry.

The Poachie Range, located in the Pb boundary zone in western Arizona, merits a separate discussion. Bryant et al. (2001) argued that the ~1680 Ma granites there are a continuation of the plutonic complex found in the Ivanpah and Cerbat Mountains and represent the eastern edge of the Mojave province. Wooden and DeWitt (1991) suggest that these mountains are on the eastern edge of their Pb boundary zone between the Mojave and Arizona provinces. The presence of Mojave-type Δ_{Jerome} values in this range has been used by Duebendorfer et al. (2006) and Duebendorfer (2015) to delineate the Bagdad block, a rifted block of Mojave crust that was at the leading edge of the Mojave-Yavapai collision. The T_{DM}'s measured in the Poachie Complex by Bennett and DePaolo (1987), however, are not characteristic of the Mojave province, as they are younger than 1760 Ma in many locations—a character that is more consistent with an Arizona affinity for these rocks (province 3). Our proposed crustal boundary in western Arizona is located at the western edge of the Pb boundary zone, west of the Poachie Range. The isotopic complexity of this range—and of the Pb boundary zone in general—likely has a tectonic origin but is beyond the scope of our study. Readers are referred to Duebendorfer (2015) for a more detailed review of the literature on this area.

This leads us to a second insight. With our redefined boundaries, province 1 is no longer continuous but, rather, is divided into two parts (northern Nevada/Utah and southern California) by province 2 (fig. 7). Most of the petrologic and geochronologic studies on which the character of the Mojave province is based have been undertaken in southern California (e.g., Wooden and Miller 1990; Bender et al. 1993; Barth et al. 2000; Strickland et al. 2013). The continuation of province 1 into northern Nevada and Utah has been based on results from Farmer and DePaolo (1984). These authors obtained T_{DM}'s between 1500 and 600 Ma in their study using mineralized granites of Cretaceous and Tertiary age (black dots in fig. 3). Even though their T_{DM}'s are <2000 Ma, these data were included in province 1 owing to their low initial $\varepsilon_{\mathrm{Nd}}$ values. The lack of data from central Nevada means that there is a large gap in the available data between southern California and northern Nevada and Utah (fig. 3). Ramo and Calzia (1998) showed that samples from Death Valley all have T_{DM}'s > 2100 Ma and negative initial $\varepsilon_{\mathrm{Nd}}$. The northernmost location with Mojave affinities is the Panamint Mountains (PmM in fig. 2; tables 4, S1). Given that no sample with $T_{\mathrm{DM}} \geq$ 2000 Ma has been described in Nevada or Utah, we therefore suggest that the northern part of province 1 does not constitute a continuation of the classic Mojave province of southern California.

The plutons from our group 1 have characteristics very similar to those described by Wooden and Miller (1990) and Strickland et al. (2013) in the Ivanpah Valley of southern California. These studies argue that the plutonic suite and deformed metamorphic rocks described there are associated with the Ivanpah orogeny. If the plutons from group 1 are part of this arc, then the area defined as province 2 in this study, with T_{DM} = 1800–2000 Ma, may correspond to an east-west-oriented crustal transition zone at the northern edge of the Mojavia microplate (Condie 1992). The observed T_{DM}'s could reflect mixtures between the older Mojave crust (which yields T_{DM} > 2000 Ma) and contemporaneous mantle-derived material (e.g., Arndt and Goldstein 1987). The Ivanpah orogeny (Wooden and Miller 1990; Strickland et al. 2013) has been considered a continuation of the 1760 Ma Yavapai arc (Karlstrom and Humphreys 1998; Whitmeyer and Karlstrom 2007), but this suture is located farther west, in Arizona. Duebendorfer (2015) has proposed that the Ivanpah orogeny occurred separate from the Yavapai orogeny, as the western and eastern Mojave blocks amalgamated. However, this would require an approximately north-south arc rather than the observed east-west one. This leads us to suggest that our province 2 represents instead the northern boundary of the Mojave terrane. It likely represents a south-dipping subduction zone, as the arc should develop on the overriding plate (fig. 3).

1450–1400 Ma Anorogenic Magmatic Event. We propose that the 1450–1400 Ma anorogenic magmatic event in the southwestern United States is not as widespread as previously thought (Anderson 1983; Anderson and Bender 1989). Our data suggest that plutons of this age may be limited or even absent in the Mojave province. The new U-Pb ages reported here are unexpected because the sampled plutons have long been considered part of the 1450–1400 Ma episode of plutonism (fig. 1; Stewart and Carlson 1978; Anderson 1983; Anderson and Bender 1989). However, these plutons (and others in the area) had been assigned an age of 1425 ± 25 Ma on the basis of personal communications or correlation with plutons with similar petrographic characteristics that were dated by Rb-Sr whole-rock isochrons (Stewart and Carlson 1978; Anderson 1983).

Even though we have dated only four of the 11 granites proposed to be Mesoproterozoic in the classic compilation of Anderson and Bender (1989), only one of these plutons—a biotite granite located in the Marble Mountains of southern California (MM in fig. 2)—was dated by U-Pb zircon analysis (1450 ± 20 Ma; Silver and McKinney 1962). However, the authors of that study stated that the U-Pb systematics appeared disturbed, producing a great dispersion in the measured ages. This leads us to regard this published age as inconclusive. Gleason et al. (1994) obtained a discordant age of 1419.2 ± 3.4 Ma for the Barrel Spring pluton of the Piute Mountains (PM in fig. 2), while Goodge and Vervoort (2006) reported an unpublished age of ~1400 Ma (no error given) for a pluton in the Turtle Mountains (TM in fig. 2). The Bowman Wash and Parker Dam granites in the Whipple Mountains (WM in fig. 2) were dated by U-Pb zircon analysis by Anderson (1983) at 1407 ± 4 and 1401 ± 5 Ma, respectively. However, these plutons are located in the Pb boundary zone (Wooden and DeWitt 1991), not in the Mojave province proper (it should be noted that they are located on the western edge of this zone, but there are no Pb measurements in this area to accurately define its boundaries). The scarcity of Mesoproterozoic plutons contrasts with the Hualapai Mountains and the Poachie Range of western Arizona, which contain several plutons with ages of 1450–1400 Ma (Bryant et al. 2001).

Regional Tectonic Regime during the Mesoproterozoic. The ~1400 Ma Rb-Sr ages that are widespread in this region (Kessler 1976) are within error of the U-Pb zircon ages of group 2 and may reflect a metamorphic or thermal event associated with the emplacement of this pluton. The Gold Butte U-Pb zircon age also overlaps with the age of the Southern Granite and Rhyolite province found in Texas and Oklahoma (province with age of 1.38 Ga in fig. 1; Anderson 1983; Karlstrom and Humphreys 1998). Nyman et al. (1994) and Sims and Stein (2003) proposed the existence of a Mesoproterozoic orogeny in the western United States at ~1400 Ma. Although Shaw et al. (2001), Cather et al. (2005), and Jones et al. (2010) described deformation in Colorado and New Mexico with ages of ~1400 Ma, no tectonic events have been documented in southern Nevada around this time. The main constraint on the timing and extent of this event in southern Nevada was the presence of shear zones in the Beer Bottle Pass pluton (part of our group 1) located in the Lucy Gray Range (Duebendorfer and Christensen 1995). We now know that this pluton is older, and we conclude that these shear zones, inferred to be formed in a transpressional tectonic setting (Duebendorfer and Christensen 1995; Karlstrom and Humphreys 1998), are likely related to the Ivanpah orogeny instead.

Conclusions

U-Pb dating of zircon shows that granites from Gold Butte, Davis Dam, the Lucy Gray Range, and the Newberry Mountains, all previously thought to be part of the transcontinental 1450–1400 Ma anorogenic plutonic event, instead represent two episodes of plutonism with crystallization ages of ~1680 and ~1370 Ma. We suggest that the 1680 Ma granites, long considered anorogenic, are instead related to the Ivanpah orogeny. This division is also reflected in Nd and Pb isotope compositions. For the 1680 Ma granites, Nd model ages combined with positive initial ε_{Nd} values suggest that the protolith was extracted from the mantle at ~1850 Ma. The ~1370 Ma granites have negative initial ε_{Nd} values, suggesting significant crustal heritage in the granitic magma. We propose crustal boundaries defined by Nd and Pb isotopes that are consistent with each other and define the western edge of a region of isotope mixing related to the accretion of the Mojave and Yavapai terranes. These internally consistent boundaries represent a hypothesis that can be tested by further sampling in the region. Besides the crustal boundary between the Yavapai and Mojave terrane, usually considered to be roughly north-south in western Arizona, we propose a northern boundary to the Mojave province that extends into southern Nevada and California along an east-west trend. Furthermore, this boundary is marked by a series of ~1680 Ma postorogenic plutons. On the basis of these new results, we propose that the Mojave terrane is restricted to southern California and does not extend north to the Wyoming province, as previously suggested (Bennett and DePaolo 1987; Whitmeyer and Karlstrom 2007).

ACKNOWLEDGMENTS

We thank the University of Arizona LaserChron Center for use of its facilities, S. H. Kim and J. Hanley for assistance and guidance during sample processing, L. Bolge and A. Hartman for assistance with the isotope analyses, the Lamont-Doherty Earth Observatory Summer Intern Program for facilitating interactions with undergraduate students involved in this project, and ConocoPhillips for its generous financial support. We thank E. M. Duebendorfer and J. L. Anderson for thoughtful and constructive reviews. This article is Lamont-Doherty Earth Observatory contribution number 7963.

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