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U-PB GEOCHRONOLOGY OF PROTEROZOIC IGNEOUS AND METASEDIMENTARY ROCKS IN SOUTHERN NEW MEXICO: POST-COLLISIONAL S-TYPE GRANITE MAGMATISM

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Abstract— U-Pb zircon ages, major element geochemistry, and Nd isotopic data are presented from several localities in the southern part of the Proterozoic Mazatzal province of southern New Mexico, excluding the Burro and San Andres Mountains. These data indicate that the bulk of granitic magmatism in the study area occurred at 1655 Ma, and that the granites are largely undeformed or only locally deformed. This group of igneous rocks is statistically younger than ~1675 Ma orthogneisses, indicating that a regional deformational event occurred between 1675–1655 Ma. The 1655 Ma granites are leucocratic with high SiO_2 and Al_2O_3 and low MgO, have both biotite and muscovite, and thus are S-type granites. Nd isotopic compositions of three samples ranges from ε_{Nd} = 1.1 to –2.0, but no useful mantle model ages were obtained owing to Sm/Nd modification after crystallization. We present a model for their generation as crustal melts following a collision. Our data also show that 1460 Ma plutons are present in the Fra Cristobal Range, Organ Mts., Antelope Hill in the southern San Andres Mountains, and likely at San Diego Mountain. This even was accompanied by metamorphism as indicated by younger zircon growth in granites at Cookes Peak and by metamorphic titanite growth at Mud Mountain. These new ages provide additional information regarding the development of the southern Mazatzal province.

INTRODUCTION

Proterozoic rocks of southern New Mexico are part of the Mazatzal province, long considered a type example of continental growth by accretion of arc rocks (e.g., Karlstrom and Bowring, 1988). The Mazatzal province of Laurentia (Fig. 1) includes rocks ranging from about 1680 Ma to approximately 1630 Ma in New Mexico, southwestern Arizona, and northern Sonora, Mexico (Karlstrom et al., 2004; Amato et al., 2008). Two long-accepted aspects of the Mazatzal province have been more recently called into question. The first is that the Mazatzal province represents a juvenile arc system; this model is problematic in light of Hf isotopic studies (e.g., Grambling et al., 2016) and general petrographic and lithologic considerations, some of which will be highlighted here. The second hypothesis is that it accreted to the Yavapai province during the Mazatzal orogeny that started around 1.65 Ga (e.g., Karlstrom and Bowring, 1988). The Mazatzal orogeny was considered part of the progressive accretion of several crustal blocks that resulted in the growth of Laurentia between 1.7 and 1.1 Ga (Karlstrom et al., 2001). This is also controversial in light of the suggestion that ~1.4 Ga tectonism may have played a role in the deformation along the suture between the Yavapai and Mazatzal provinces (Daniel et al., 2013), and if it was a continental arc, there is no need to invoke a collision, as the arc would have been formed on Laurentia.

The Amato Research Group at New Mexico State University has attempted to address these questions across a broad transect stretching from the Burro Mountains in southwestern New Mexico to the extensive exposures of the San Andres Mountains along the Rio Grande rift of central New Mexico (Fig. 2). In previous contributions, we have focused on the geology of the Burro Mountains including both ~1.6 Ga (Amato et al., 2008) and ~1.4 Ga events (Amato et al., 2011). The key questions we are trying to address include: (1) What is the age of the Mazatzal province crust in southern New Mexico; (2) Does the Mazatzal province in southern New Mexico represent juvenile volcanic arc crust? (3) Is the Mazatzal province

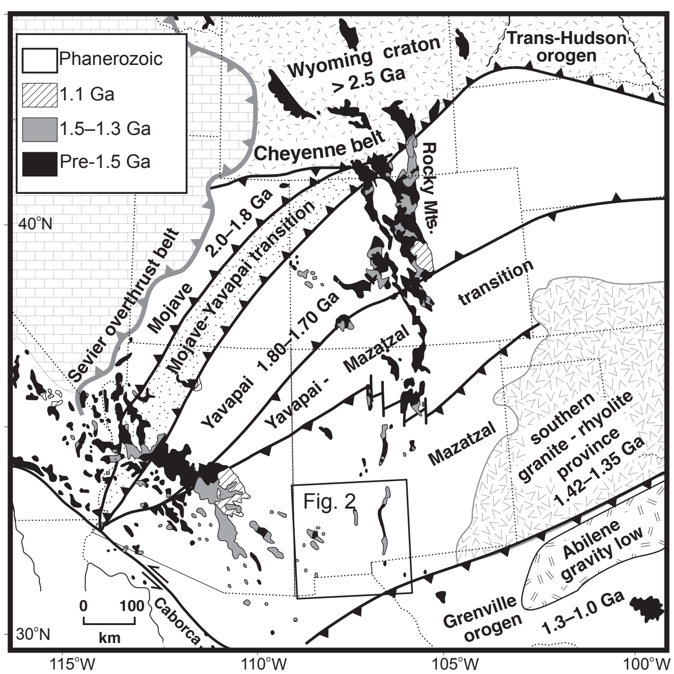

FIGURE 1. Subdivisions of southwestern Laurentia into Precambrian provinces, showing exposures of Proterozoic rocks and tectonic province boundaries. Modified from Karlstrom et al. (2004).

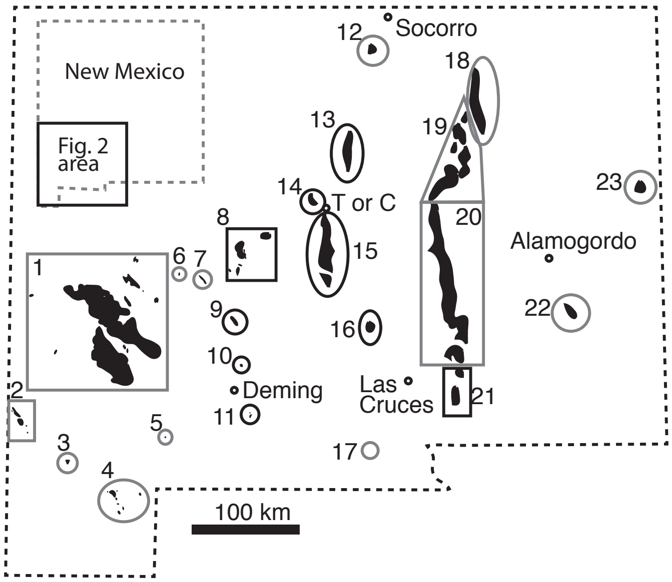

FIGURE 2. Proterozoic localities in southern New Mexico. Localities outlined in gray are not part of this study. Localities outlined in black are part of this study: 8-Kingston; 9-Cookes Peak; 10-Fluorite Ridge; 11-Florida Mtns.; 13-Fra Cristobal Mtns.; 14-Mud Mountain; 15-Caballo Mtns.; 16-San Diego Mtn.; 21-Organ Mtns./Antelope Hill. Map compiled from Condie and Budding (1979), Condie (1981), Woodward (1970), and Bauer and Pollock (1993). See Data Repository for the full list.

lithologically and isotopically homogeneous, or can it be subdivided into smaller blocks that originated in different tectonic settings? and (4) What is the age of initiation and duration of the Mazatzal orogeny? In this paper, we present U-Pb ages of igneous and metasedimentary rocks from southern New Mexico (Fig. 2) and present a new model for their formation involving crustal melting following accretion.

REGIONAL GEOLOGY

Proterozoic growth of Laurentia involved the progressive accretion of large lithostratigraphic terranes onto Archean provinces (e.g., Condie, 1982). The terranes involved in this accretion in New Mexico include the Yavapai province, and the Mazatzal province (Fig. 1). The Yavapai province mainly consists of 1.8–1.7 Ga juvenile arc rocks with some older material and the Mazatzal province consists of 1.70–1.65 Ga arc rocks and metasedimentary rocks (Karlstrom and Bowring, 1988). Abundant plutons dated at 1.68–1.65 Ga intrude the metamorphosed volcanic and sedimentary rocks (Karlstrom et al., 2004) and are generally considered to be juvenile arc rocks based on geochemical studies (e.g., Condie, 1982; Bennett and DePaolo, 1987).

The Mazatzal orogeny was the result of the collision of the Mazatzal province with the Yavapai province. The timing of these collisions is controversial. It has been suggested that these were discrete events and that the Yavapai orogeny occurred around 1.72–1.68 Ga and the Mazatzal orogeny occurred at 1.65 Ga (Karlstrom et al., 2004). Some workers have presented evidence that the Mazatzal orogeny occurred over a protracted period between 1.65–1.60 Ga (e.g., Williams et al., 1999). The Paleoproterozoic igneous rocks of the Mazatzal province in southern New Mexico can be divided into two broad age groups based on Amato et al. (2008) and a compilation in Karlstrom et al. (2004): 1680–1650 Ma and 1630–1620 Ma. In general, the older group consists of rocks that are pervasively deformed, and the younger group includes rocks that are undeformed or only locally deformed. This study evaluates this prior assessment.

Mapping of Precambrian rocks in southern New Mexico (Fig. 2) is available from various publications (e.g., Woodward, 1970; Condie and Budding, 1979). U-Pb ages from the San Andres, Florida, and Burro Mountains were reported by Amato et al. (2008) showing a range from 1674–1617 Ma in these areas. Additional details on the geology of individual regions can be found in Ottenfeld (2015). In this paper, we focus on rocks from the ~1.65 Ga episode of magmatism and associated sedimentary rocks.

METHODS

Major elements were analyzed by XRF and Nd isotopes were analyzed by TIMS, both at New Mexico State University. U-Pb geochronology was carried out using laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) at the U. of Arizona and the U. of California at Santa Barbara. SHRIMP (sensitive high-resolution ion microprobe) dating was conducted for two samples at the Stanford–US Geological Survey Facility. The analytical techniques and data reduction procedures are discussed in Amato et al. (2008). All uncertainties are reported in the text at the 2σ level. We use a 10% uncertainty and discordance filter. We use the weighted mean of $^{207}Pb/^{206}Pb$ ages because it minimizes the effects of Pb loss, and for mostly concordant data, concordia intercepts are not as helpful. A summary of the ages obtained is reported in Table 1 and the complete dataset and concordia diagrams are in the online Data Repository (http://nmgs.nmt.edu/repository/index.cfml?rid=2018003).

LITHOLOGY AND GEOCHRONOLOGY RESULTS

Igneous Rocks

Granite sample 13KD-11 from the Kingston District is massive, brown to pink, medium- to coarse-grained and weathers red-brown, with irregular black fine-grained hornblende. The granite has granophyric texture with intergrowths of K-feldspar and quartz and exsolution lamellae in the K-feldspar. Plagioclase, biotite altered to chlorite, zircon, and Fe-Ti oxides are present in minor amounts. It has a weighted mean zircon $^{207}Pb/^{206}Pb$ age of 1659±12 Ma (Fig. 3A).

The basement rocks at Fluorite Ridge, approximately 15 km south of Cookes Peak are mostly biotite granite, but some amphibolite was locally present. The granite is altered. The Proterozoic granite (sample 12CR-04) yielded two populations of zircon. The main group has a weighted mean $^{207}Pb/^{206}Pb$ age of 1638±18 Ma, and the younger group is 1480±23 Ma (Fig. 3B). Neither group has distinctive U-Th ratios suggesting metamorphism. Based on the relative proportion of 1.6 Ga vs. 1.4

TABLE 1. Summary of U-Pb ages from Proterozoic rocks.

Sample #	Area	Rock Type	Mineral	Date run	Lab	Machine	Beam (μm)	n	Wtd. Mean Age	Error (2σ)	MSWD	Easting	Northing
13KD-04	Kingston	Graywacke	Zircon	11/19/13	ALC	LA-ICPMS	35	16	1671	13	0.6	243847	3642638
13KD-05	Kingston	Conglomerate	Zircon	11/19/13	ALC	LA-ICPMS	35	45	1663	14	0.5	243951	3642580
13KD-11	Kingston	Granophyre	Zircon	11/19/13	ALC	LA-ICPMS	35	20	1659	12	0.3	245361	3649192
13Cookes-4	Cookes Peak	Granodiorite	Zircon	11/19/13	ALC	LA-ICPMS	35	11	39.1	3.4	0.1	244001	3603681
12CR-04	Fluorite Ridge	Granite	Zircon	10/23/15	ALC	LA-ICPMS	30	7	1480	23	1.6	244620	3587288
12CR-04	Fluorite Ridge	Granite	Zircon	10/23/15	ALC	LA-ICPMS	30	23	1638	18	1.7	244620	3587288
01FM-3	Florida	Foliated granite	Zircon	10/23/15	ALC	LA-ICPMS	20	23	1624	11	0.4	249824	3560587
15FC-1	Fra Cristobal	Granite	Zircon	10/23/15	ALC	LA-ICPMS	20	9	1452	21	0.5	303008	3695432
15FC-1	Fra Cristobal	Granite	Zircon	10/23/15	ALC	LA-ICPMS	20	4	1652	31	0.3	303008	3695432
15FC-2	Fra Cristobal	Granite	Zircon	5/12/17	ALC	LA-ICPMS	20	5	1464	21	0.3	302458	3698311
13MS-03	Mud Mountain	Granite	Zircon	2/24/13	UCSB	LA-ICPMS	30	4	1688	37	1.2	284245	3671221
13MS-06	Mud Mountain	Granite	Zircon	5/12/17	ALC	LA-ICPMS	20	23	1653	15	1.3	284196	3671279
13MS-09	Mud Mountain	Amphibolite	Titanite	9/22/14	ALC	LA-ICPMS	40	15	1427	24	0.6	284307	3670997
13MS-09	Mud Mountain	Amphibolite	Zircon	3/12/14	ALC	LA-ICPMS	40	4	1656	15	0.6	284307	3670997
13MS-10	Mud Mountain	Granite	Zircon	4/27/15	ALC	LA-ICPMS	20	11	1651	21	0.5	284349	3671012
13CM-11	Caballo	Granite	Zircon	3/11/14	ALC	LA-ICPMS	40	27	1666	14	1.3	289602	3648536
13CM-14	Caballo	Quartzite	Zircon	3/11/14	ALC	LA-ICPMS	40	17	1644	14	2.7	289636	3648061
03SD-1	San Diego	Granite	Zircon	2/1/05	ALC	LA-ICPMS	25	15	1259	120	7.4	314674	3608836
06OR-1	Organs	Granite	Zircon	3/1/07	Stanford	SHRIMP	30	11	1440	25	0.5	350411	3587030
09SA-15d	San Andres	Granite	Zircon	6/14/11	Stanford	SHRIMP	30	5	1445	10	0.3	360938	3589351
09SA-15d	San Andres	Granite	Zircon	3/4/10	ALC	LA-ICPMS	30	10	1445	15	0.3	360938	3589351

Note: All localities use UTM datum WGS84, zone 13S.

Ga zircons, in which only six out of 30 grains are 1.4 Ga, we are interpreting that the intrusive age is 1638 Ma and that the younger grains represent younger overgrowths or metamorphic zircon with atypical U-Th ratios. Pb loss is not likely as both groups are concordant, and the $^{207}Pb/^{206}Pb$ ages are typically not sensitive to recent Pb loss.

The Florida Mountains sample, 01FM-3, is a foliated biotite granite. Zircons were analyzed by LA-ICPMS. The $^{207}Pb/^{206}Pb$ weighted mean age is 1624±11 Ma (Fig. 3C). This age is the same as the SHRIMP age reported by Amato and Mack (2012), and thus we are confident of its accuracy.

Both samples of Proterozoic granite at the Fra Cristobal Mountains (samples 15FC-1 and 15FC-2) are fine to medium grained, pink, and consist of quartz, plagioclase, perthitic orthoclase, biotite mainly altered to chlorite, and muscovite. Both samples yielded two populations of $^{207}Pb/^{206}Pb$ ages. The weighted mean age of the older population (n=4) in sample 15FC-1 is 1652±31 Ma and the younger population (n=9) is 1452±21 Ma (Fig. 3D). Sample 15FC-2 has a main population at 1464±21 Ma, two older grains at 1646 Ma and 1745 Ma, and several younger grains, four of which have $^{238}U/^{206}Pb$ dates of 562-418 Ma (Fig. 3E). Despite this complexity, we suggest that the majority of the zircons in both samples are ~1.45 Ma and that this represents the intrusive age of the pluton. A combined weighted mean age using zircons from both samples yields 1457±17 Ma (MSWD=0.5). The older grains are likely xenocrystic, and the Early Paleozoic grains may represent zircon that formed during regional Cambrian magmatism.

Sample 13MS-03 is a fine-grained pink granite from Mud Mountain with perthitic microcline, plagioclase, quartz, muscovite, and minor biotite. It yielded a weighted mean $^{207}Pb/^{206}Pb$ age of 1688±37 Ma (Fig. 3F). Sample 13MS-06 is a medium-grained pink granite with biotite (altered to chlorite) and minor muscovite as accessory phases. It yielded a weighted mean $^{207}Pb/^{206}Pb$ age of 165±15 Ma (Fig. 3G). Another granite (sample 13MS-10) is coarse-grained and light pink. Quartz, K-feldspar, and plagioclase are major phases with muscovite, biotite, and epidote present. Sample 13MS-10 was analyzed with LA-ICPMS. Zircons yield a weighted mean $^{207}Pb/^{206}Pb$ age of 1651±21 Ma (Fig. 3H). A combined weighted mean age using the ~1.65 Ga zircons from all three samples yields 1655±13 Ma (MSWD=0.85).

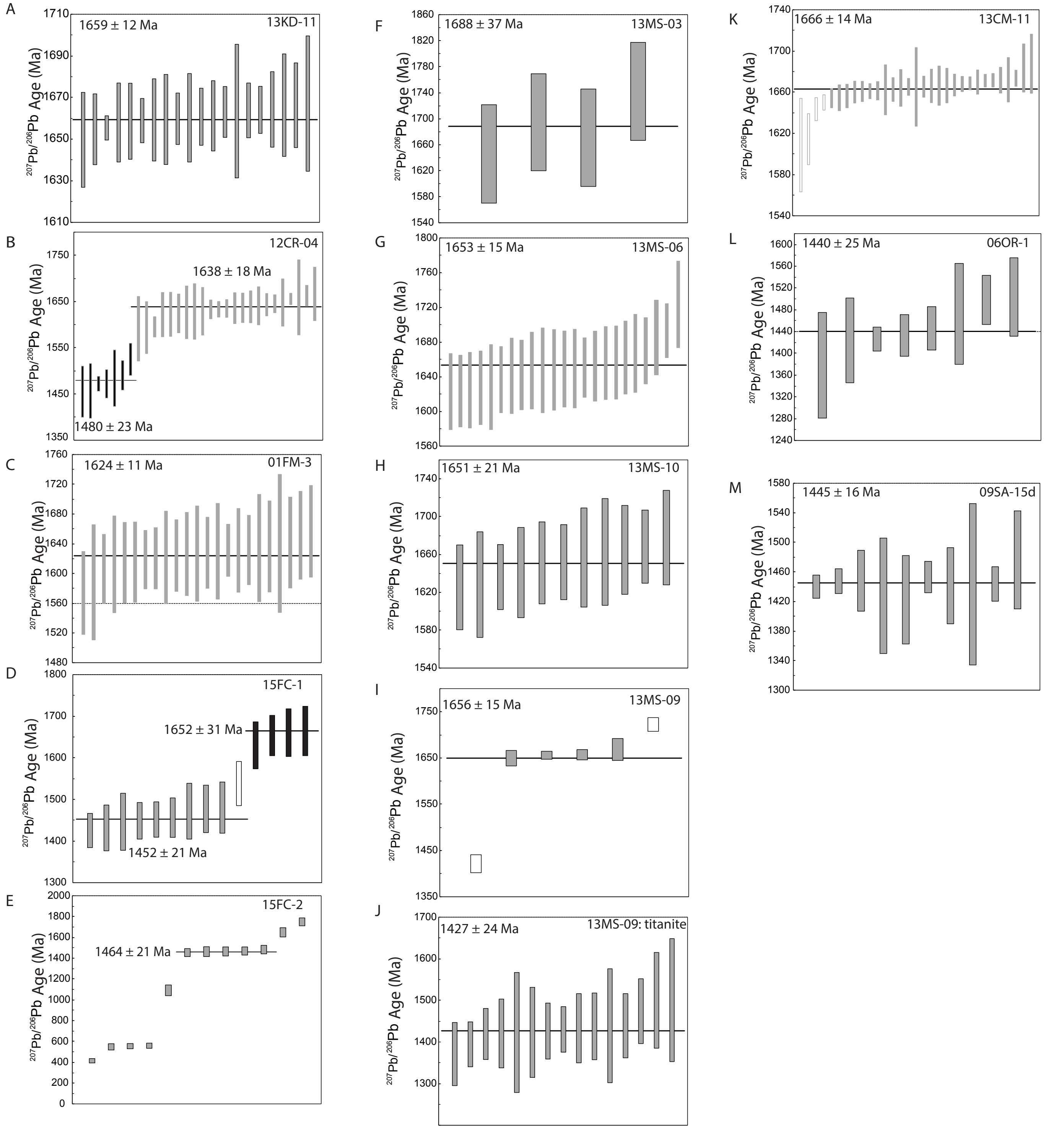

FIGURE 3. **A-M**) U-Pb geochronology plots.

The amphibolite at Mud Springs (sample 13MS-09) is dark green to black and is generally unfoliated with small patches that are weakly foliated. Hornblende makes up 70% of the rock and is 1–2 mm long. Plagioclase makes up 20%, has been altered to sericite and is 1 mm in diameter. Rounded quartz grains make up 10% of the rock. The youngest population included four zircons that produced a weighted mean $^{207}Pb/^{206}Pb$ age of 1656±15 Ma, which is the preferred age (Fig. 3I). Titanite from the same amphibolite sample was analyzed and yielded a preferred weighted mean $^{207}Pb/^{206}Pb$ age of 1427±24 Ma (Fig. 3J). This is interpreted as the age of metamorphism.

In the Caballo Mountains, Proterozoic granite varies from crumbly to massive and is locally foliated. The granite (sample 13CM-11) weathers a medium tan to gray color, and is fine- to medium-grained, consisting of quartz, K-feldspar, and plagioclase, with muscovite and biotite. Garnet are present in trace amounts. This sample yielded a weighted mean $^{207}Pb/^{206}Pb$ zircon age of 1666±14 Ma (Fig. 3K).

The granite at San Diego Mountain (sample 03SD-1) is pink, fine to medium grained, and rich in perthitic microcline, plagioclase, and quartz, with minor chloritized biotite. Zircons were extremely metamict with unusually high concentrations of common Pb as indicated by low $^{206}Pb/^{204}Pb$ ratios, and thus we were unsuccessful at determining an age for this sample.

The granite from the Organ Mountains (sample 06OR-1) is medium grained with perthitic potassium feldspar, plagioclase, quartz, and minor biotite. This sample yielded a weighted mean $^{207}Pb/^{206}Pb$ age of 1440±25 Ma (Fig. 3L). This is similar to the previously published SHRIMP age of 1462±28 Ma from the same sample (Rioux et al., 2016).

About 10 km due east of the Organ Mountains sample is a granite at a site called Antelope Hill. Despite being mapped as the same unit as the Organ Mountains sample (Seager, 1981), this intrusion is notably coarser grained, with perthitic K-feldspar crystals reaching 5 cm in length. Quartz is abundant and plagioclase is less abundant than in sample 06OR-1. Biotite is more abundant, comprising approximately 15% of the rock. This sample (15SA-15d) was dated using both SHRIMP and LA-ICPMS. The ages are consistent, with the SHRIMP age yielding a weighted mean $^{207}Pb/^{206}Pb$ age of 1445±10 Ma, and the LA-ICPMS age is 1445±16 Ma (Fig. 3M), incorporating both random and systematic errors.

Metasedimentary Rocks

In the Kingston District, metasedimentary rocks include conglomerate, schist, phyllite, and graywacke. The metagraywacke (sample 13KD-04) is fine-grained and consists of a quartz/plagioclase matrix (80%) with subordinate quartz and plagioclase. Sixteen U-Pb zircon analyses yielded a single peak at 1671 Ma, which is interpreted as the maximum depositional age (Fig. 4A). The youngest grain was 1662±9 Ma (1σ). No older peaks were present. The metaconglomerate (sample 13KD-05) has a fine-grained matrix with quartz grains and polycrystalline quartz lithics (30%) up to 5 mm and subhedral. Plagioclase grains are present along with trace white mica, and chlorite. This sample yielded a youngest zircon age peak at 1663 Ma (n=45), which is interpreted as the maximum depositional age (Fig. 4B). Two older grains have ages of 1839 Ma and 2681 Ma.

Biotite quartzite from the Caballo Mountains (sample 13CM-14) is thinly interlayered with amphibolite, weathers a light gray, and is medium-grained. The layers are ~10 cm thick. There are several granitic pebble clasts (~1 cm). Quartz makes up 90% of the rock, with minor plagioclase and biotite. The youngest zircon population consists of eight grains with a peak $^{207}Pb/^{206}Pb$ age of 1641 Ma (Fig. 4C). Other peaks are at 1691 Ma (n=3) and 2370 Ma (n=1). One grain has an age of 1230 Ma, but it is not clear what its significance is.

GEOCHEMISTRY RESULTS

Four of the ~1.6 Ga igneous rocks were analyzed for major element geochemistry (Table 2). Most have high SiO_2 (>71 wt.%) Al_2O_3 (>13%), Na_2O, K_2O, with low MgO (<2%) and CaO (<1%). Sample 13MS-06 is more intermediate with SiO_2 of 67%.

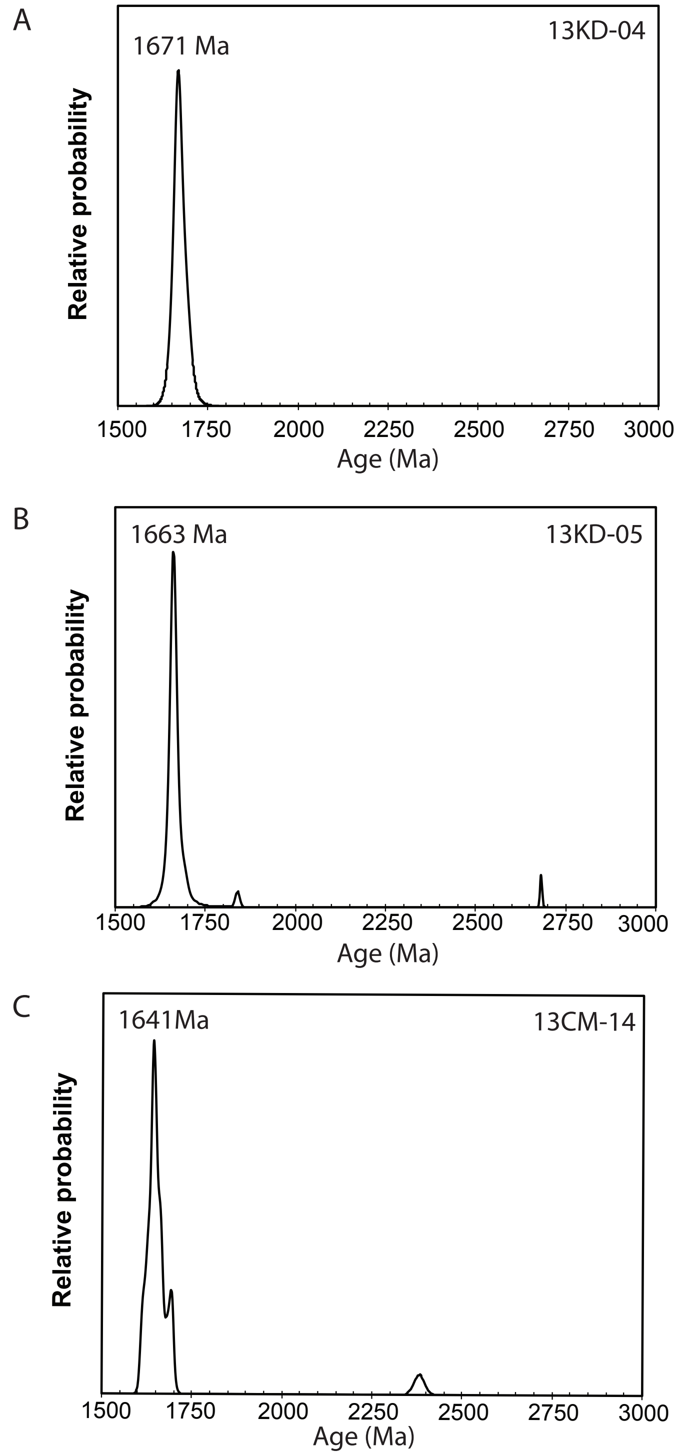

FIGURE 4. Probability density plots for U-Pb detrital zircon ages from metasedimentary rocks. **A**) Metagraywacke from Kingston District; **B**) Metaconglomerate from Kingston District; **C**) Biotite quartzite from Caballo Mountains.

Nd isotopic composition was measured on three ~1.65 Ga granite samples (Table 3). The three samples have similar ε_{NdT} initial values ranging from 1.1 to -2.0. Depleted mantle model

TABLE 2. Whole rock chemistry as determined by XRF.

Sample weight %	13KD-04	13KD-11	13MS-06	13MS-10	13CM-11
SiO_2	71.6	75.8	66.9	74.7	76.1
TiO_2	0.4	0.3	0.4	0.2	0.3
Al_2O_3	16.2	11.7	17.4	14.1	13.0
Fe_2O_{3*}	3.8	2.9	2.4	1.1	2.3
MnO	0.1	0.1	BD	BD	BD
MgO	1.5	0.1	0.7	0.3	0.3
CaO	0.7	0.5	1.3	0.5	0.7
Na_2O	1.5	3.3	3.7	4.0	3.6
K_2O	4.8	4.7	7.8	5.7	4.3
P_2O_5	0.1	0.0	0.0	0.1	0.0
Total	**100.7**	**99.4**	**100.7**	**100.8**	**100.6**

Notes: Whole-rock major element concentrations were determined by X-ray fluorescence spectroscopy. Samples were analyzed at New Mexico State University, using a spectrograph equipped with an end-window Rh target X-ray tube. Rigaku ZSX wavelength-dispersive spectrograph equipped with an end-window Rh target X-ray tube.

*Fe was measured as Fe_2O_3.

BD indicates below detection limits

ages (DePaolo, 1981) however range from 1.9 Ga to 2.9 Ga. It is likely that these values are not accurate given the extreme ages and variability. However, it is notable that none of the model ages are close to the intrusive age, raising the possibility that older crust was involved (e.g., Hill and Bickford, 2001) or that post-intrusive modifications to the Sm/Nd ratio occurred (e.g., Arndt and Goldstein, 1987).

DISCUSSION

The Timing of Paleoproterozoic Deformation

The ages of intrusive rocks from this study indicate that the ~1.6 Ga magmatism in the Las Cruces region occurred between 1659±12 and 1624±11 Ma. With the exception of the Florida Mountains gneiss, the other four areas (Mud Mt., Cookes Range, Kingston, and Caballo Mtns.) all form a population at about 1655 Ma, with the Florida Mountains sample being statistically younger. The San Andres Mountains and Burro Mountains, based on previously published work, have both older (~1675 Ma; Amato et al., 2008) and additional samples in the younger group, around 1630 Ma (Rämö et al., 2003; Amato et al., 2008). Without the high precision of TIMS (thermal ionization mass spectrometry) dates, it is still somewhat difficult to ensure that there is not a continuum of magmatism. Based on the existing data, taking into consideration all of the uncertainties, we postulate that the southern Mazatzal province was created through magmatism during three episodes: (1) 1680 Ma, consisting of felsic intrusive rocks, now orthogneiss, and mafic igneous rocks, now amphibolite; (2) 1655 Ma, consisting mainly of two-mica granites that are undeformed or locally deformed; and (3) 1630 Ma generally undeformed granites and gabbro that may have formed during rifting (Rämö et al., 2003; Amato et al., 2008).

After another decade of geochronology and field observations, the hypothesis of Amato et al. (2008), that the presence or absence of foliations in plutonic rocks could be used to date the Mazatzal orogeny at ~1650 Ma likely needs to be modified. Instead, we suggest that gneisses, with strong, continuous foliation and alternating light and dark bands, rather than foliated granites, with oriented biotite, are a better indication of a regional deformational event. In the San Andres Mountains, gneisses with clear igneous origins are part of the 1680 Ma event (Amato et al., 2016), and thus it remains likely that there is a regional deformational event that predates the 1655 Ma granitic magmatism that is the focus of this study. Foliated granites younger than 1655 Ma, such as the Florida Mountains granite, likely formed in more localized shear zones rather than in a widespread regional event. This may relate to the waning of regional deformation, and an increase in partitioned deformation in shear zones during regionally lower temperatures past the peak timing of magmatism and deformation. Thus, in our model, a major deformational event did occur, but it likely happened between 1680 Ma and 1655 Ma rather than between 1655 Ma and 1633 Ma as previously postulated (Amato et al., 2008).

TABLE 3. Nd isotopic data.

Sample	Rock	t (Ma)	Sm (ppm)	Nd (ppm)	$(^{143}Nd/^{144}Nd)m$	$(^{147}Sm/^{144}Nd)a$	$(^{143}Nd/^{144}Nd)i$	ε_{Nd}	T_{dm} (Ga)
13MS-10	Mud Springs Granite	1651	3.8	18.8	0.512	0.122	0.511	1.13	1.92
13CM-11	Caballo Granite	1666	5.3	23.8	0.512	0.136	0.511	0.41	2.06
13KD-11	Kingstone Granite	1659	12.8	44.8	0.512	0.173	0.510	-1.99	2.94

Similarly, the Amato et al. (2008) hypothesis that undeformed rocks in the aureole of a 1633 Ma gabbro in the Burro Mountains provided a constraint on the timing of the Mazatzal orogeny is also likely not valid. Further work in that region suggests that the metamorphism in the vicinity of the gabbro may not be a contact aureole, but a continuum of low-grade metamorphism affecting rocks away from the main region of high-temperature metamorphism that formed during the 1460 Ma magmatic event (Amato et al., 2016). In the San Andres Mountains, however, clear evidence for contact metamorphism at 1630 Ma is present (Ottenfeld and Amato, 2015).

The Origin of the 1655 Ma Granites

The 1655-1625 Ma igneous rocks in this study are mainly granites. Mineralogy is typically quartz, plagioclase, and perthitic K-feldspar. Accessory minerals are biotite (in all samples) and muscovite at Mud Mountain and Caballo Mountains. Kingston also has hornblende, but amphibole is rare in most areas. Most of the accessory phases are <10% of the total sample, Thus, the majority of the samples are leucogranites with two micas, consistent with the S-type granites classification.

The ~1655 Ma granites of the southern Mazatzal province are similar in composition to the Himalayan leucogranites (e.g., Guo and Wilson, 2012) in that they are leucogranites, they have two micas (biotite and muscovite), with high SiO_2 and Al_2O_3 and low MgO. The Himalayan granites formed through crustal melting in response to the India/Asia collision (Le Fort et al., 1987), and the time lag between the onset of collision (50 Ma; Zhu et al., 2005) and granite formation (23 Ma; Harrison et al., 1997) was approximately 25 my. If the ~1680 Ma deformed gneisses of the southern Mazatzal province (Amato et al., 2008; Amato et al., 2016) are an indication of the maximum age of the timing of a collision, then the ~1655 Ma two-mica granites have, potentially, a similar time lag. Unfortunately, the 2σ uncertainty of the LA-ICPMS dates preclude a more precise determination of the gap between these two groups. Provisionally, we suggest that the 1655 Ma granites formed through crustal melting following a collision that occurred sometime after 1680 Ma. The generation of the Mazatzal two-mica granites up to 20 my after collision might be explained by higher heat flow in the Paleoproterozoic than in the Cenozoic (e.g., Nyblade and Pollack, 1993), upwelling of asthenosphere as the result of slab breakoff following the collision (e.g., Sylvester, 1998), or shear heating along major suture zones (e.g., Harrison et al., 1998).

Amphibolite and Metasedimentary Rocks

An exception to the granitic compositions is the amphibolites that are common but volumetrically subordinate in the southern Mazatzal province. The amphibolites have two origins. One group has igneous protoliths and consist mainly of hornblende and plagioclase, whereas the other group likely has a sedimentary origin as it contains abundant quartz and locally, biotite (Amato et al., 2008). The igneous amphibolite forms boudins in granitic gneiss (Amato et al., 2008) and massifs within metasedimentary successions (Amato et al., 2016). The sedimentary amphibolite forms thin (1-10 cm) interlayers with the metasedimentary rocks including schist and quartzite. Igneous amphibolite was dated at 1684±14 Ma in the Burro Mountains (Amato et al., 2008). The amphibolite in this study, sample 13MS-09, has ~10% quartz and we infer a sedimentary origin. The zircon age is 1656±15 Ma. This is interpreted as a maximum depositional age of the sedimentary protolith.

The other metasedimentary rocks in this study are conglomerate, graywacke, and quartzite, with schist being a common constituent as well (though undated in this study). These samples have maximum depositional ages of 1671 Ma, 1663 Ma, and 1644 Ma, respectively. The two older ages come from the Kingston district and we suggest that they form the country rock for the granite, though field relations are ambiguous, and it is possible they represent younger rocks. The quartzite with 1644 Ma maximum depositional age in the Caballo Mountains is interlayered with amphibolite at a fine scale (Fig. 4) and these rocks either overlap with or are slightly younger than the age of the granite, suggesting that it may be younger than the granite. A more detailed study of the metasedimentary rocks in the Mazatzal province is underway to more fully understand the relationships between the igneous and sedimentary rocks in the region. Regardless, the samples dominantly yield a single youngest peak with few, if any, older grains present.

Mesoproterozoic Magmatism and Metamorphism

The volumetrically significant 1.4 Ga magmatic event forms a wide belt that stretches 1000's of km across Laurentia (e.g., Goodge and Vervoort, 2006; Amato et al., 2011). Throughout much of the province, these rocks are generally undeformed, but in other areas, including northern New Mexico, they are interpreted as being syntectonic (e.g., Nyman et al., 1994). In the Burro Mountains, granodiorite and biotite leucogranites yield ages around 1460 Ma, and these are associated with high-T metamorphism and deformation (Amato et al., 2011).

In this study, four ~1.4 Ga granites were dated. In the Fra Cristobals, despite some complexity, the large intrusion that makes up the bulk of the Proterozoic basement appears to be 1457±17 Ma. The Organ Mountains granite is less precisely dated at 1440±25 Ma, but this overlaps in age with the 1445±15 Ma coarse granite at Antelope Hill in the southern San Andres Mountains. We suggest that the Organ Mountains granite is a finer-grained, marginal border phase of the Antelope Hill granite. The San Diego Mountains granite is poorly dated but we are leaning towards an interpretation that it also is a ~1.4 Ga pluton. These ages are coeval with the numerous ~1460 Ma granites in the Burro Mountains (Amato et al., 2011) and demonstrate that the bulk of ~1.4 Ga magmatism in southern New Mexico occurred around 1460–1440 Ma. None of the 1.4 Ga plutons in this study are deformed, whereas some of the 1.4 Ga granites in the Burro Mountains are deformed. Thus, there is no clear evidence that the postulated ~1.4 Ga Picuris orogeny (Daniel et al., 2013) affected this region.

Metamorphism also occurred in this area. The Cookes Range granite has some evidence of younger zircon growth at

1480±23 Ma, and the metamorphic titanite from Mud Mountain yielded an age of 1427±24 Ma. It is likely that this age represents the age of crystallization during reheating (Frost et al., 2000).

CONCLUSIONS

The main conclusions from this study of Proterozoic rocks in southern New Mexico are: (1) There is a fundamental difference between ~1675 Ma strongly deformed orthogneisses and ~1655 Ma granites, most of which are undeformed or weakly deformed. We suggest that "foliated granites" should not be used as a constraint on regional deformation, but the older group of orthogneisses can provide important limits on the age of the collisional event that we suggest occurred after 1675 Ma and before 1655 Ma. (2) Many of the 1655 Ma leucogranites are "S-type" two-mica granites and as such were generated through partial melting of the crust. We suggest that the Himalayan leucogranites provide an analog in which granite genesis followed a collision. (3) Nd isotopic compositions of three samples range from 1.1 to –2.0, but calculation of model ages yields no consistent age population, suggesting either a range of ages of older crust, or modification of the Sm-Nd ratio subsequent to their formation; regardless, we regard model ages of >1.9 Ga unlikely to represent actual lower crust ages. (4) ~1460 Ma granites are present in the Fra Cristobals, Organ Mts./Antelope Hill, and likely at San Diego Mountain. This even was accompanied by metamorphism as indicated by younger zircon growth in older granites at Cookes Peak and by metamorphic titanite growth at Mud Mountain, likely related to heating during ~1.4 Ga magmatism. (5) Although amphibolite with igneous protoliths is present in the region, most amphibolite has sedimentary protoliths as indicated by the presence of quartz and the exposures indicating preserved interlayers of amphibolite and quartzite at centimeter scales. The metasedimentary rocks have maximum depositional ages consistent with being host rocks for the 1655 Ma granites, such as in the Kingston district, as well as some indication that others may be coeval or younger than the igneous rocks, as in the Caballo Mountains. (6) Future work should be directed at TIMS dating of key orthogneiss and 1655 Ma granites to constrain the timing of the collision and the duration of the lag between collision and crustal melting.

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REFERENCES

Amato, J.M., Boullion, A.O., Serna, A.M., Sanders, A.E., Farmer, G.L., Gehrels, G.E., and Wooden, J.L., 2008, The evolution of the Mazatzal province and the timing of the Mazatzal orogeny: Insights from U-Pb geochronology and geochemistry of igneous and metasedimentary rocks in southern New Mexico: Geological Society of America Bulletin, v. 120, p. 328-346.

Amato, J.M., Heizler, M.T., Boullion, A.O., Sanders, A.E., McLemore, V.T., Toro, J., and Andronicos, C.L., 2011, Syntectonic 1.46 Ga magmatism and rapid cooling of a gneiss dome in the southern Mazatzal province: Burro Mountains, New Mexico: Geological Society of America Bulletin, v. 123, p. 1720-1744.

Amato, J.M., Ottenfeld, C., and Heizler, M.T., 2016, The Mazatzal province in southern New Mexico: U-Pb dating of Paleoproterozoic rocks to assess magmatism, deposition, metamorphism, and deformation: Geological Society of America Annual Meeting, Abstracts with Programs, v. 48, no. 7, doi: 10.1130/abs/2016AM-281074.

Arndt, N.T., and Goldstein, S.L., 1987, Use and abuse of crust-formation ages: Geology, v. 15, p. 893-895.

Bennett, V.C., and DePaolo, D.J., 1987, Proterozoic crustal history of the western United States as determined by neodymium isotopic mapping: Geological Society of America Bulletin, v. 99, p. 674-685.

Condie, K.C., 1982, Plate-tectonics model for Proterozoic continental accretion in the southwestern United States: Geology, v. 10, p. 37-42.

Condie, K.C., and Budding, A.J., 1979, Geology and geochemistry of Precambrian rocks, central and south-central New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir, v. 25, p. 1-58.

Daniel, C.G., Pfeifer, L.S., Jones, J.V. III, and McFarlane, C.M., 2013, Detrital zircon evidence for a non-Laurentian provenance, Mesoproterozoic (ca. 1490-1450 Ma) deposition and orogenesis in a reconstructed orogenic belt, northern New Mexico, USA: Defining the Picuris orogeny: Geological Society of America Bulletin, v. 125, p. 1423-1441.

DePaolo, D.J., 1981, Neodymium isotopes in the Colorado Front Range and crust-mantle evolution in the Proterozoic: Nature, v. 291, p. 193-196.

Eisele, J., and Isachsen, C.E., 2001, Crustal growth in southern Arizona: U-Pb geochronologic and Sm-Nd isotopic evidence for addition of the Paleoproterozoic Cochise Block to the Mazatzal province: American Journal of Science, v. 301, p. 773-797.

Frost, B.R., Chamberlain, K.R., and Schumacher, J.C., 2000, Sphene (titanite): phase relations and role as a geochronometer: Chemical Geology, v. 172, p. 131-148.

Goodge, J.W., and Vervoort, J.D., 2006, Origin of Mesoproterozoic A-type granites in Laurentia: Hf isotope evidence: Earth and Planetary Science Letters, v. 243, p. 711-731.

Grambling, T.A., Holland, M.E., Karlstrom, K.E., and Grambling N.L., 2016, Paired Zircon U-PB-Hf Isotope Analysis of the Yavapai-Mazatzal Boundary in New Mexico: Evidence for a Mazatzal Continental Arc System: Geological Society of America Abstracts.

Guo, Z., and Wilson, M., 2012, The Himalayan leucogranites: Constraints on the nature of their crustal source region and geodynamic setting: Gondwana Research, v. 22, p. 360–376.

Harrison, T.M., Grove, M., Lovera, O.M., and Catlos, E.J., 1998, A model for the origin of Himalayan anatexis and inverted metamorphism: Journal of Geophysical Research, Solid Earth, v. 103, p. 27017-27032.

Harrison, T.M., Lovera, O.M., and Grove, M., 1997, New insights into the origin of two contrasting Himalayan granite belts: Geology, v. 25, p. 899-902.

Karlstrom, K.E., Åhäll, K.-I., Harlan, S.S., Williams, M.L., McLelland, J., and Geissman, J.W., 2001, Long-lived (1.8–1.0 Ga) convergent orogen in southern Laurentia, its extensions to Australia and Baltica, and implications for refining Rodinia: Precambrian Research, v. 111, p. 5-30.

Karlstrom, K.E., Amato, J.M., Williams, M.L., Heizler, M., Shaw, C.A., Read, A.S., and Bauer, P., 2004, Proterozoic tectonic evolution of the New Mexico region: A synthesis, *in* Mack, G.H., and Giles, K.A., eds., The Geology of New Mexico: A Geologic History: New Mexico Geological Society, p. 1-34.

Karlstrom, K.E., and Bowring, S.A., 1988, Early Proterozoic assembly of tectonostratigraphic terranes in southwestern North America: Journal of Geology, v. 96, p. 561-576.

Le Fort, P., Cuney, M., Deniel, C., France-Lanord, C., Sheppard, S.M.F., Upreti, B.N., and Vidal, P., 1987, Crustal generation of the Himalayan leucogranites: Tectonophysics, v. 134, p. 39-57.

Nyblade, A.A., and Pollack, H.N., 1993, A global analysis of heat flow from Precambrian terrains: Implications for the thermal structure of Archean and Proterozoic lithosphere: Journal of Geophysical Research, Solid Earth, v. 98, p. 12207-12218.

Nyman, M.W., Karlstrom, K.E., Kirby, E., and Graubard, C.M., 1994, Mesoproterozoic contractional orogeny in western North America: Evidence from ca. 1.4 Ga plutons: Geology, v. 22, p. 901-904.

Ottenfeld, C.F., 2015, The Paleoproterozoic Mazatzal province in southern New Mexico: Magmatism, sedimentation, metamorphism, and deformation [M.S. Thesis]: Las Cruces, New Mexico State University, 180 p.

Ottenfeld, C.F., and Amato, J.M., 2015, U-Pb geochronology and tectonic significance of arc-related Proterozoic rocks in southern New Mexico: New Mexico Geological Society, Annual Spring Meeting Abstracts, p. 43.

Rämö, O.T., McLemore, V.T., Hamilton, M.A., Kosunen, P.J., Heizler, M., and Haapala, I., 2003, Intermittent 1630-1220 Ma magmatism in central Mazatzal province: New geochronologic piercing points and some tectonic implications: Geology, v. 31, p. 335-338.

Rioux, M., Farmer, G.L., Bowring, S.A., Wooton, K.M., Amato, J.M., Coleman, D.S., and Verplanck, P., 2016, The link between volcanism and plutonism in epizonal magma systems: High-precision U-Pb zircon geochronology from the Organ Mountains caldera and batholith, New Mexico: Contributions to Mineralogy and Petrology, v. 171, p. 1-22.

Sylvester, P.J., 1998, Post-collisional strongly peraluminous granites: Lithos, v. 45, p. 29-44.

Williams, M.L., Karlstrom, K.E., Lanzirotti, A., Read, A.S., Bishop, J.L., Lombardie, C.E., Pedrick, J.N., and Wingstead, M.B., 1999, New Mexico middle crustal cross sections: 1.65 macroscopic geometry, 1.4 Ga thermal structure, and continued problems in understanding crustal evolution: Rocky Mountain Geology, v. 34, p. 53-66.

Woodward, L.A., 1970, Precambrian rocks of southwestern New Mexico: New Mexico Geological Society, Guidebook 21, p. 27-31.

Zhu, B., Kidd, W.S.F., Rowley, D.B., Currie, B.S., and Shafique, N., 2005, Age of initiation of the India-Asia collision in the east-central Himalaya: Journal of Geology, v. 113, p. 265-285.

Supplemental data can be found at http://nmgs.nmt.edu/repository/index.cfml?rid=2018003

Steam from a hot spring entering the Rio Grande below Leasburg Dam. Photograph by Peter A. Scholle.