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

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ABSTRACT

New U-Pb zircon ages, geochemistry, and Nd isotopic data are presented from three localities in the Paleoproterozoic Mazatzal province of southern New Mexico, United States. These data help in understanding the source regions and tectonic setting of magmatism from 1680 to 1620 Ma, the timing of the Mazatzal orogeny, the nature of postorogenic magmatism, Proterozoic plate tectonics, and provide a link between Mazatzal subblocks in Arizona and northern New Mexico. The data indicate a period from 1680 to 1650 Ma in which juvenile felsic granitoids were formed, and a later event between 1646 and 1633 Ma, when these rocks were deformed together with sedimentary rocks. No evidence of pre-1680 Ma rocks or inherited zircons was observed. The igneous rocks have $\varepsilon_{Nd}(t)$ from –1.2 to +4.3 with most between +2 and +4, suggesting a mantle source or derivation from similar-aged crust. Nd isotope and trace element concentrations are consistent with models for typical arc magmatism. Detrital zircon ages from metasedimentary rocks indicate that sedimentation occurred until at least 1646 Ma. Both local and Yavapai province sources contributed to the detritus. All of the samples older than ca. 1650 Ma are deformed, whereas undeformed porphyroblasts were found in the contact aureole of a previously dated 1633 Ma gabbro. Regionally, the Mazatzal orogeny occurred mainly between 1654 and 1643 Ma, during final accretion of a series of island arcs and intervening basins that may have amalgamated offshore. Rhyolite magmatism in the southern Mazatzal province was coeval with gabbro intrusions at 1633 Ma and this bimodal magmatism may have been related to extensional processes following arc accretion.

Keywords: Mazatzal province, New Mexico, Proterozoic, U-Pb geochronology, zircons, neodymium.

INTRODUCTION

The Mazatzal province of Laurentia is marked by exposures of Paleoproterozoic rocks younger than 1.70 Ga in New Mexico, southwestern Arizona (United States), and northern Sonora, Mexico (Karlstrom and Bowring, 1988). This province mainly consists of juvenile arc-related igneous rocks and associated sedimentary rocks that were involved in a major deformational event known as the Mazatzal orogeny (Wilson, 1939; Silver, 1965, 1978; Karlstrom and Bowring, 1988; Conway and Silver, 1989; Karlstrom et al., 2004) that affected rocks of the Mazatzal and Yavapai provinces (Fig. 1). Geochronologic data suggest the Mazatzal orogeny occurred from 1.65 to 1.60 Ga (Karlstrom and Bowring, 1993; Luther et al., 2006) or 1.65–1.63 Ga (Eisele and Isachsen, 2001). The Mazatzal orogeny was part of the progressive accretion of several crustal blocks that resulted in the growth of Laurentia between 1.7 and 1.1 Ga.

Evaluation of the formation of the Mazatzal province and the timing of the Mazatzal orogeny has been hindered by the scarce outcrops of Paleoproterozoic crust in the southwestern United States and northern Sonora, widespread high-temperature overprinting by ca. 1.48–1.38 Ga (hereafter ca. 1.4 Ga) magmatism and deformation, and extensive Laramide and Paleogene magmatism and deformation. Much of what we know about the Mazatzal orogeny comes from detailed studies in southern Colorado, northern New Mexico, and parts of Arizona (Silver, 1978; Condie, 1982; Karlstrom et al., 1987, 1990; Eisele and Isachsen, 2001). There have been relatively few detailed structural and geochronological studies of Paleoproterozoic rocks in southern New Mexico, yet this area provides an excellent opportunity to understand the formation and deformation of the Mazatzal province because Proterozoic

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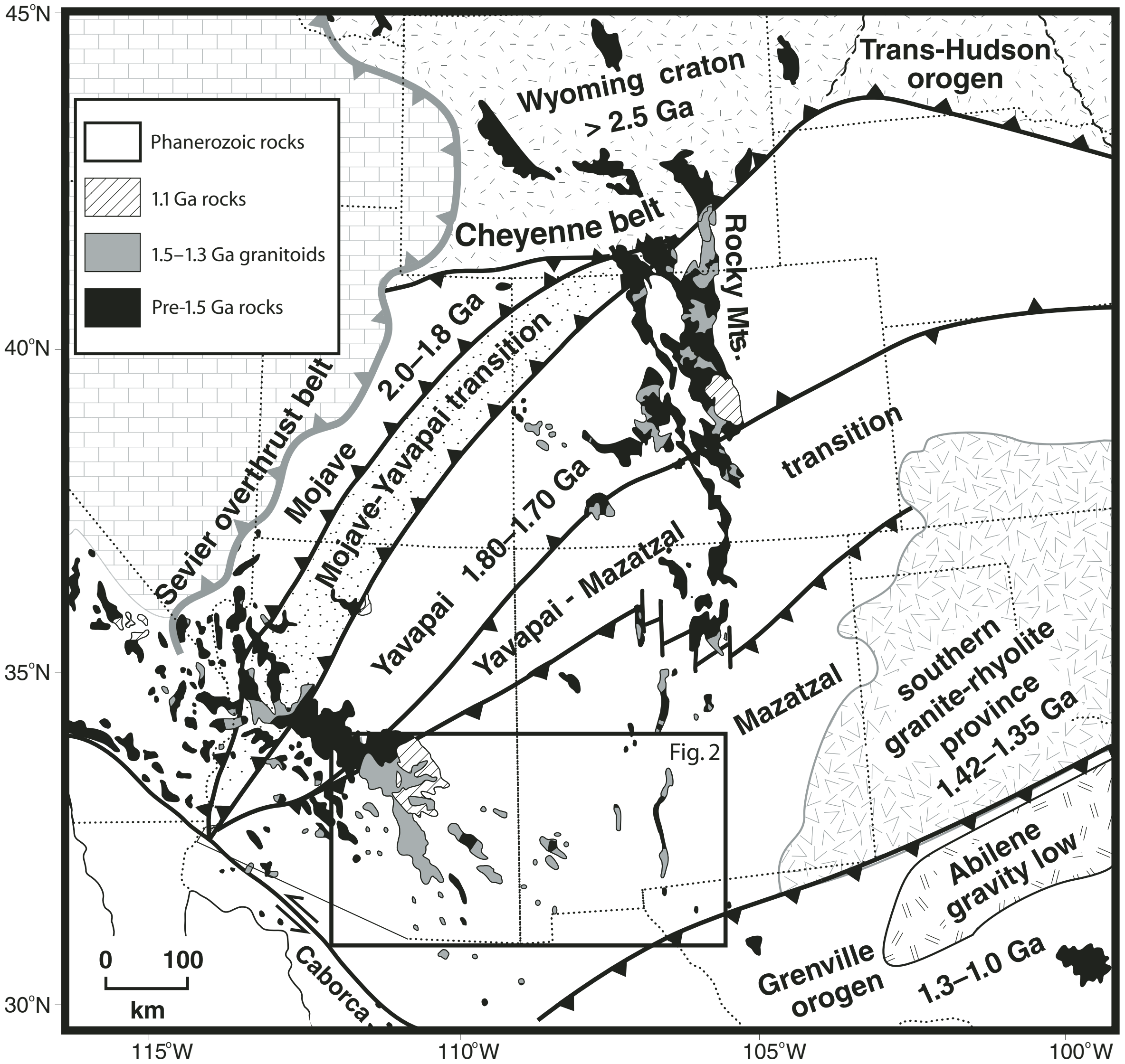

Figure 1. Subdivisions of southwestern Laurentia into Precambrian provinces, showing exposures of Proterozoic rocks. Box shows location of Figure 2. Modified from Karlstrom et al. (2004).

rocks are well exposed in a series of normal fault blocks related to Tertiary extensional tectonism. In addition, the intensity of ca. 1.4 Ga deformation is significantly less than in other areas of the Mazatzal province (Amato et al., 2006; Boullion, 2006).

The Mazatzal province is considered a type example of continental growth by accretion of arc rocks, yet key questions remain concerning the origin of Mazatzal province crust and the timing of the Mazatzal orogeny. These questions 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 lithologically and isotopically homogeneous, or can it be subdivided into smaller blocks that originated in different tectonic settings? (4) What is the age of initiation and duration of the Mazatzal orogeny?

Resolving these questions will refine the arc-accretion model for Proterozoic crustal growth and help determine the global relevance of the model. The localities in this project provide a link between previous work in southeastern Arizona and northern New Mexico. Trace element geochemical studies and Nd isotopic studies of Mazatzal-age crust in the southwestern United States also provide an opportunity to understand Proterozoic lithospheric growth and the nature of mid-crustal rocks that underlie a large part of southern Laurentia. A more comprehensive description of Mazatzal province geology will also help with tectonic reconstructions of the Rodinia supercontinent (Dalziel, 1991; Moores, 1991; Karlstrom et al., 1999). Finally, this study is an assessment of Proterozoic tectonic processes. In this paper we describe the geology of three areas in southern New Mexico with Proterozoic exposures: the Burro Mountains, the Florida Mountains, and the San Andres Mountains (Fig. 2). We use geochemistry and U-Pb zircon dating of deformed plutonic rocks and detrital zircons from metasedimentary rocks to address these questions and integrate our results with the regional Mazatzal province data set.

REGIONAL GEOLOGY

The generally accepted model for the Proterozoic growth of Laurentia involves the progressive

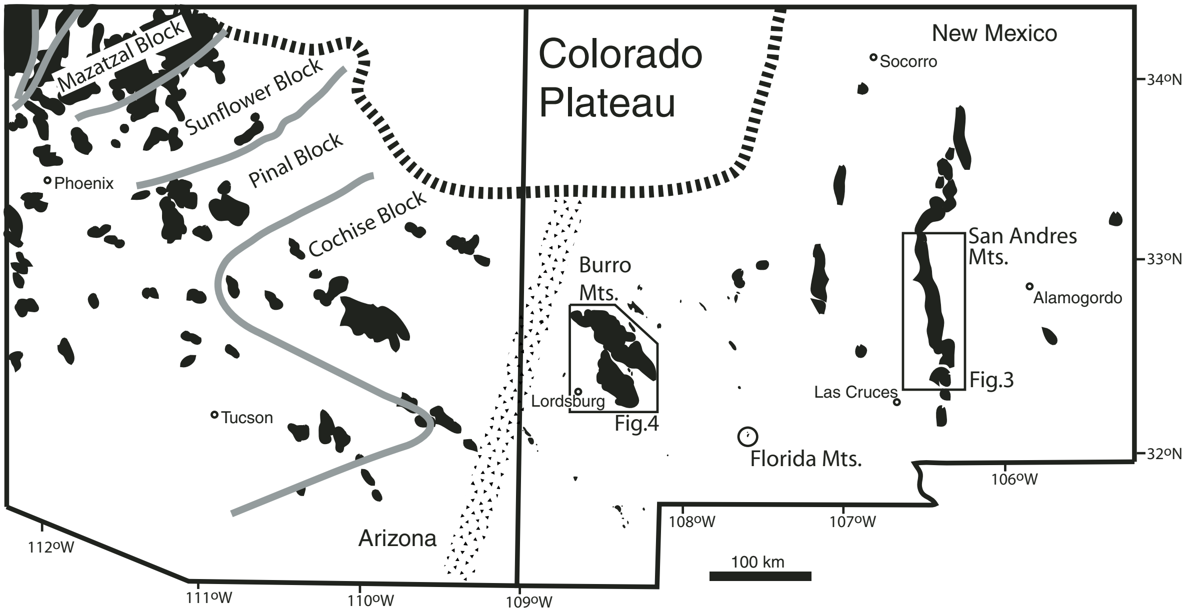

Figure 2. Proterozoic localities in southwestern New Mexico and southeastern Arizona, showing the outcrop areas of Proterozoic rocks (black) and postulated boundaries between tectonostratigraphic blocks based on Karlstrom and Bowring (1988) and Eisele and Isachsen (2001). Stippled line near the Arizona–New Mexico border is drawn to reflect the approximate boundary between the Cochise block and the Proterozoic rocks of southern New Mexico. See text for details. Geology is after Woodward (1970), Condie and Budding (1979), Condie (1981), Karlstrom and Bowring (1988), Eisele and Isachsen (2001), and Karlstrom et al. (2004).

accretion of juvenile island arc terranes onto Archean provinces (Condie, 1982; Karlstrom et al., 1987; Karlstrom and Bowring, 1988). The terranes involved in this accretion have been divided into three lithospheric blocks or provinces based on the age and isotopic characteristics of the crust (Karlstrom et al., 2004): the Mojave province, the Yavapai province, and the Mazatzal province (Fig. 1). The Mojave province has intrusive rocks similar in age to the Yavapai province, but they are much more isotopically evolved (Rämö and Calzia, 1998); also, metasedimentary and volcanic rocks contain Archean derived material (Farmer et al., 2005). 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 sedimentary rocks (Karlstrom and Bowring, 1988). The Mojave and Yavapai provinces were deformed at the same time, and the boundary between them may be diffuse mainly because of postaccretion tectonic modifications (Shaw and Karlstrom, 1999). Magnani et al. (2004) imaged a doubly vergent crustal suture at the boundary between the Yavapai and the Mazatzal province beneath the Jemez lineament. The suture is characterized by low-angle faults and structures that might account for the diffuse character of the boundary. Some igneous rocks in Arizona and Colorado have ages older than typical Yavapai or Mazatzal province ages (Hawkins et al., 1996), and these have been interpreted as evidence of Trans-Hudson Penokean crust in southwestern Laurentia (Hill and Bickford, 2001; Bickford and Hill, 2007).

There were three main orogenic events that resulted in the assembly of southwestern Laurentia. The Mojave province was accreted to the Yavapai province ca. 1730 Ma in the Ivanpah orogeny (Wooden and Miller, 1990; Duebendorfer et al., 2006; Duebendorfer et al., 2001). The Yavapai orogeny refers to accretion of arc crust beginning at 1.80 Ga culminating with accretion of the Yavapai and Mojave provinces to Laurentia (Karlstrom and Bowring, 1988; Karlstrom et al., 1990; Duebendorfer et al., 2001). 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 there were discrete events and that the Yavapai orogeny occurred ca. 1.72–1.68 Ga and the Mazatzal orogeny occurred at 1.65 Ga (Karlstrom et al., 2004). Other studies have suggested a continuum of deformation between 1.70 and 1.65 Ga (Williams et al., 1999). Some workers have presented evidence that the Mazatzal orogeny occurred over a protracted period between 1.65 and 1.60 Ga (Bowring and Karlstrom, 1990; Luther et al., 2006).

The major rock types of the Mazatzal province in northern New Mexico include 1.68–1.65 Ga volcanic rocks such as those exposed in the southern Santa Fe Range and Sandia-Manzano Mountains (Condie, 1980; Karlstrom et al., 1998). Many of these rocks are greenstones with an ophiolitic origin (Condie, 1980). Felsic volcanic rocks ranging in age from 1.70 to 1.66 Ga (Reiche, 1949; Karlstrom et al., 1998) are associated with metasedimentary rocks deposited between ca. 1.70–1.65 Ga (Grambling et al., 1988; Karlstrom et al., 2004). Abundant plutons dated as 1.68–1.65 Ga intrude the volcanic and sedimentary rocks (Karlstrom et al., 2004) and are generally considered to be juvenile arc rocks based on Nd isotopic and trace element geochemical studies (Condie, 1982; Nelson and DePaolo, 1985; Bennett and DePaolo, 1987).

In Arizona, the Mazatzal province was divided into several tectonostratigraphic terranes or crustal blocks (Fig. 2) based on their ages and tectonic histories (Karlstrom and Bowring, 1988). In southeastern Arizona, the Proterozoic rocks were further divided into the Cochise block and the Pinal block based on their age and isotopic composition (Eisele and Isachsen, 2001). The Cochise block was interpreted as a juvenile volcanic arc with intermediate to felsic volcanic rocks with ages from 1647 to 1630 Ma. These were associated with sedimentary rocks containing

TABLE 1. SAMPLES ANALYZED, METHODS USED, AND LOCATIONS

			Geochemistry		U-Pb Dating			Location		
Sample	Location	Rock type	XRF	ICPMS	ε_{Nd}(t)	LA-MC-ICPMS	SHRIMP	Zone	E	N
DMC-1	San Andres Mountains	Foliated granite	X	X			X	13S	352830	3634955
SA-2	San Andres Mountains	Granite gneiss	X	X	X		X	13S	363000	3608523
SA-2C	San Andres Mountains	Granite gneiss					X	13S	362169	3607734
SAHC-1Q	San Andres Mountains	Lithic quartzite				X		13S	353065	3646023
01FM-3	Florida Mountains	Granite gneiss				X	X	13S	249835	3560393
05BM-174	Burro Mountains	Amphibolite	X					12S	730854	3615870
05BM-158	Burro Mountains	Granitic gneiss or migmatite	X		X	X		12S	728361	3617380
04BM-137	Burro Mountains	Granitic gneiss or migmatite	X	X		X		12S	732676	3618653
03BM-117	Burro Mountains	Metasedimentary migmatite	X	X	X	X	X	12S	729689	3620750
01BM-19a	Burro Mountains	Biotite-garnet schist			X			12S	725437	3621603
01BM-33	Burro Mountains	Biotite-garnet schist			X			12S	723030	3624474
01BM-9	Burro Mountains	Biotite-garnet schist				X		12S	724716	3621247
03BM-84	Burro Mountains	Quartz-muscovite schist				X		12S	715491	3623878
03BM-86	Burro Mountains	Quartz-muscovite schist				X		12S	715471	3623924
03BM-110	Burro Mountains	Metarhyolite					X	12S	728021	3622814

Notes: Locations are based on Universal Transverse Mercator Datum NAD27.
SHRIMP—sensitive high-resolution ion microprobe;
IC-MC-ICPMS—laser ablation multicollector inductively coupled plasma mass spectrometry.

1729–1630 Ma zircons. The Pinal block consists mainly of 1.68–1.65 Ga volcanic rocks and basinal metaturbidites with detrital zircon ages of 1731–1678 Ma interpreted as a continental margin accretionary prism (Eisele and Isachsen, 2001). These blocks are separated by rocks interpreted as an ophiolite sequence representing a possible suture (Swift and Force, 2001).

Although this study and further work may provide clues to divide the Mazatzal province into further subblocks, the term Mazatzal province is still useful to describe rocks that have the following characteristics: (1) igneous rocks with an age range from 1700 to 1600 Ma are present; (2) most igneous rocks have juvenile isotopic geochemical signatures; (3) sedimentary rocks associated with rhyolite volcanism were deposited from ca. 1700–1650 Ma and include locally derived detritus as well as detritus older than Mazatzal province rocks; (4) rocks older than 1650 Ma are generally pervasively deformed, whereas rocks with ages between 1650 and 1600 Ma are only locally deformed; (5) rocks are metamorphosed to greenschist or amphibolite grade, but it is unclear how much of this metamorphism occurred before 1.5–1.4 Ga; and (6) they are generally located south of an northeast-southwest–trending line that extends from southeastern Arizona to northwestern Mexico (Fig. 1).

The distribution and lithology of Precambrian rocks in southern New Mexico (Fig. 2) are known from early mapping of Proterozoic rocks in the Burro Mountains (Hewitt, 1959; Hedlund, 1978h; Condie and Budding, 1979) and San Andres Mountains (Condie and Budding, 1979) and a compilation map of the Precambrian exposures of the region (Condie, 1981). Sparse U-Pb geochronological studies (Stacey and Hedlund, 1983; Evans and Clemons, 1988; Roths, 1991) indicated that some rocks were coeval with abundant 1.5–1.4 Ga magmatism, whereas others may be related to the 1.70–1.65 Ga development of the Mazatzal province.

The Paleoproterozoic igneous rocks of the Mazatzal province in southern New Mexico can be divided into two broad age groups based on this study and an age compilation done by 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. In this study we collected rocks suspected to be older than 1.6 Ga in age for geochronology and geochemical studies from the following southern New Mexico localities: the southern San Andres Mountains, the Florida Mountains, and the Burro Mountains (Fig. 2). All of them contain exposed blocks that were uplifted during late Paleogene extension (Mack, 2004).

PALEOPROTEROZOIC ROCKS OF SOUTHERN NEW MEXICO

In this paper we focus on the Paleoproterozoic rocks of southern New Mexico because they have not been studied as extensively as coeval exposures in central and northern New Mexico, and we consider that they may help to clarify our understanding of the nature of the Mazatzal province and the timing and extent of the Mazatzal orogeny. New geologic mapping was conducted in parts of the San Andres and Burro Mountains, and samples were collected for petrology, geochronology, and geochemistry. The Florida Mountains exposures are relatively small and this area was not remapped, but one sample of granitic gneiss was collected for geochemical and geochronologic studies. Our new data are described in context of previous work by the U.S. Geological Survey and from unpublished Masters theses. All of the analyzed samples are listed in Table 1.

San Andres Mountains

The Paleoproterozoic rocks of the San Andres Mountains (Fig. 3) are exposed at the base of the eastern flank of west-tilted fault blocks below an unconformity with the Cambrian–Ordovician Bliss sandstone (Kottlowski et al., 1956; Bachman and Harbour, 1970; Condie and Budding, 1979; Seager, 1981; Roths, 1991; Vollbrecht, 1997). These include both igneous and metasedimentary rocks.

The igneous rocks include gneiss, granite, amphibolite, and metavolcanic rocks. The granite gneiss was interpreted to have a felsic igneous protolith and was previously dated as 1730 ± 130 Ma by U-Pb on multiple zircon fractions (Roths, 1991). The gneiss is strongly foliated and folded. Foliation strikes east-west and is steeply dipping. Tight to isoclinal folds have steep axial planes and fold axes that plunge gently west (Roths, 1991). Granites of Paleoproterozoic age include the Strawberry Peak pluton that was dated as ca. 1630 Ma (Vollbrecht, 1997) and a foliated granite of 1632 ± 24 Ma exposed in Dead Man Canyon (Roths, 1991). Several other granitic plutons are undeformed and likely range in age from 1.5 to 1.4 Ga, such as the 1462 ± 67 Ma Mineral Hill pluton (Roths, 1991). Amphibolite is common in the San Andres Mountains. Mineralogy includes hornblende and plagioclase with minor quartz and biotite. In some locations it is present as small boudinaged bodies within orthogneiss, and in others it is more massive. This unit has been interpreted as both flows and dikes (Vollbrecht, 1997). Metavolcanic rocks are felsic and deformed and dated as ca. 1650 Ma (Vollbrecht, 1997).

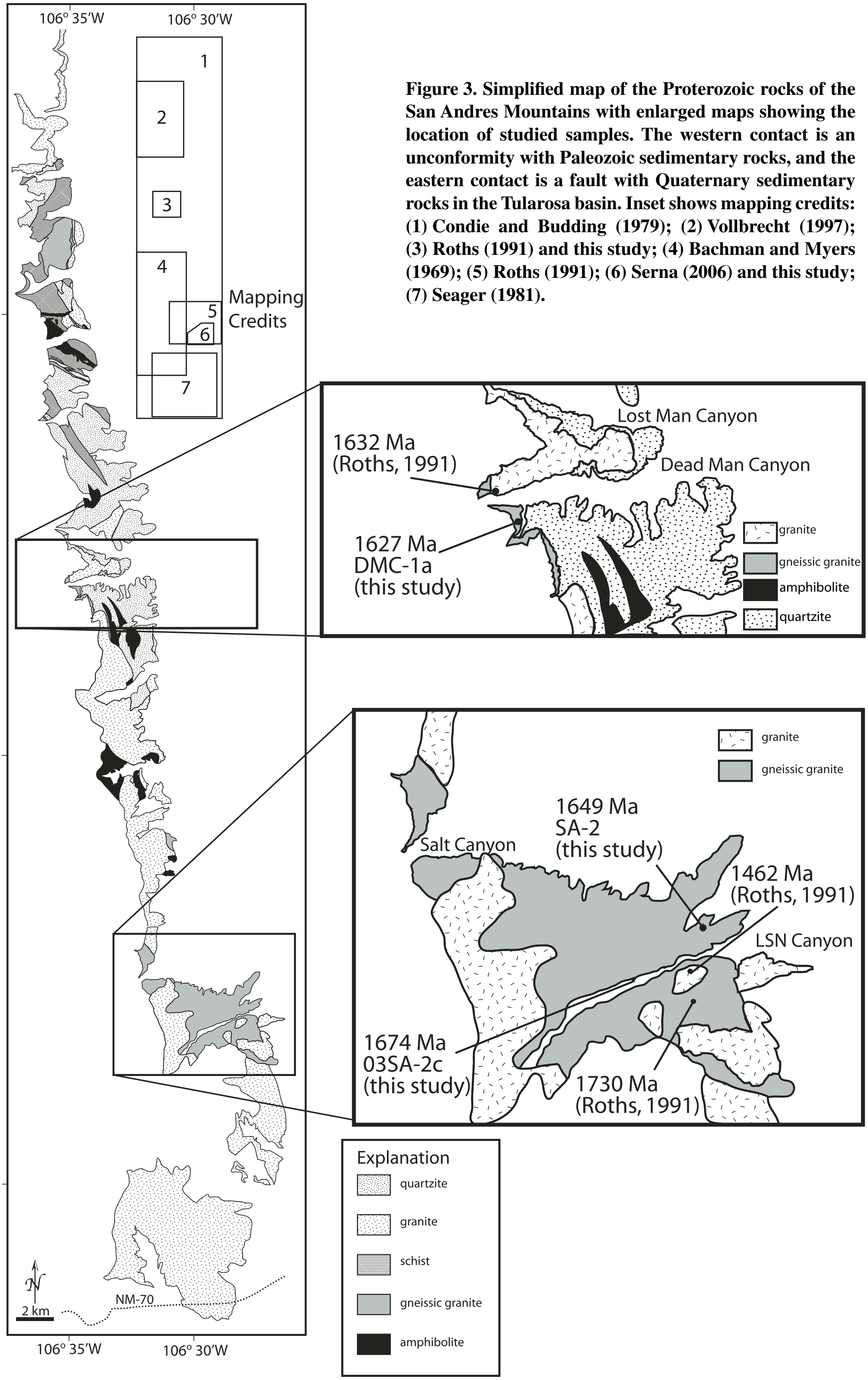

Figure 3. Simplified map of the Proterozoic rocks of the San Andres Mountains with enlarged maps showing the location of studied samples. The western contact is an unconformity with Paleozoic sedimentary rocks, and the eastern contact is a fault with Quaternary sedimentary rocks in the Tularosa basin. Inset shows mapping credits: (1) Condie and Budding (1979); (2) Vollbrecht (1997); (3) Roths (1991) and this study; (4) Bachman and Myers (1969); (5) Roths (1991); (6) Serna (2006) and this study; (7) Seager (1981).

Metasedimentary rocks in the San Andres Mountains range have been referred to as the Hembrillo Canyon succession (Alford, 1987) and consist of foliated metaconglomerate, quartzite, phyllite, and mica schist (Condie and Budding, 1979; Alford, 1987; Vollbrecht, 1997). The phyllite and schist both contain strongly foliated quartz and white mica with minor biotite, garnet, and andalusite (Vollbrecht, 1997). Quartzite has 90% quartz with minor feldspar and biotite. Other sandstones are more arksosic (Vollbrecht, 1997). Trough cross-bedding and ripple structures are preserved. Paleocurrent measurements from metasedimentary rocks yielded N40W flow and S30E flow directions (Alford, 1987). Peak regional metamorphic conditions in the metasedimentary rocks were estimated as 350 °C and 0.15–0.25 GPa with temperatures reaching 600–650 °C near intrusions (Alford, 1987).

Deformation in the San Andres Mountains includes formation of foliations in granites and metasedimentary rocks and gneissic banding in the granite gneiss. This fabric was subsequently folded in open and isoclinal folds. Intrafolial folds of thin schistose layers were reported adjacent to resistant quartzite with preserved primary structures, indicating that all metasedimentary rocks were affected by this deformation (Vollbrecht, 1997). The timing of this folding is unknown, but the formation of the foliations was interpreted to have occurred between 1650 Ma and 1630 Ma based on deformed ca. 1650 Ma metavolcanic rocks and an interpretation of late syntectonic granite emplacement at 1630 Ma (Vollbrecht, 1997).

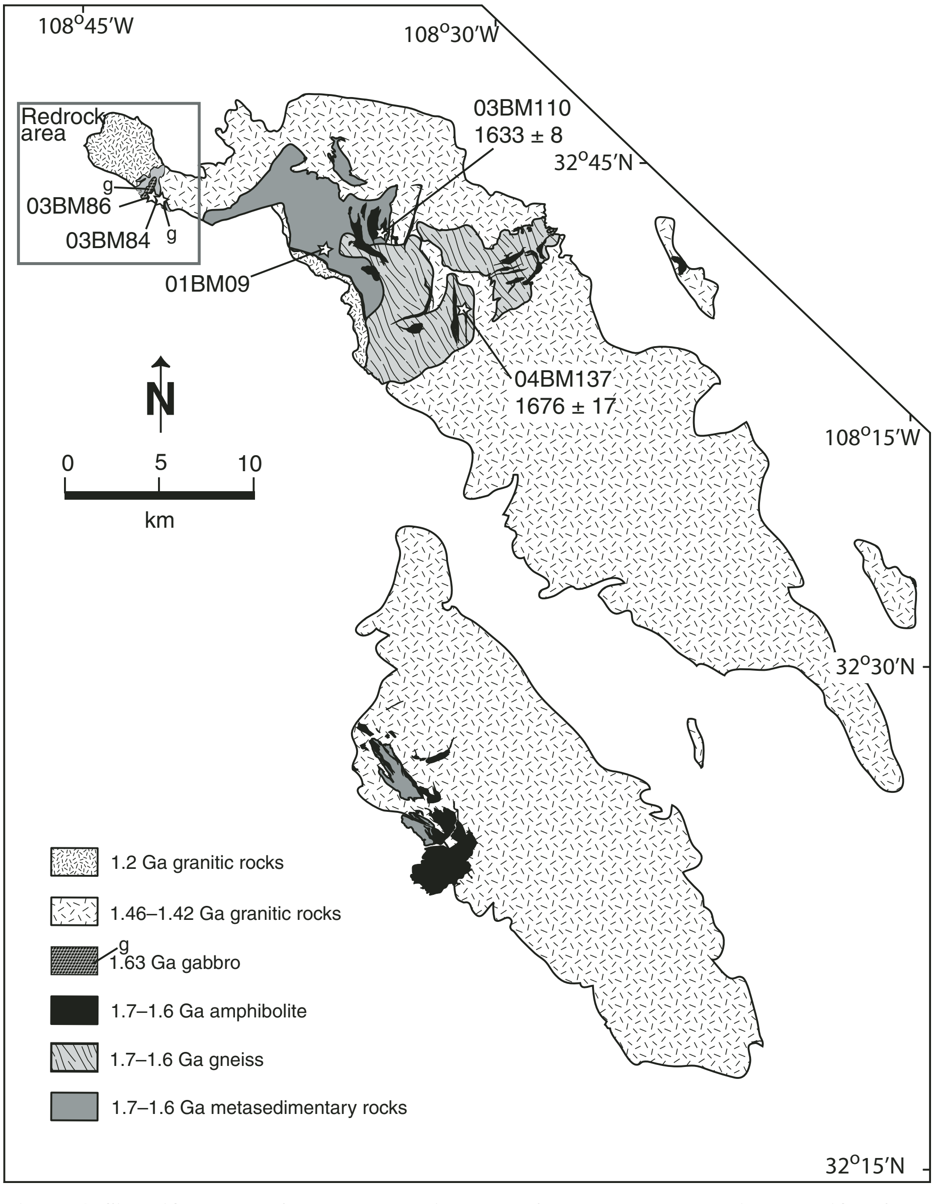

Figure 4. Simplified map of the Proterozoic rocks of the Burro Mountains. Modified from Hedlund (1978a, 1978b, 1978c, 1978d, 1978e, 1978f, 1978g, 1978h, 1980a, 1980b, 1980c), Finnell (1987), Rämö et al. (2003), and Boullion (2006).

Florida Mountains

The Paleoproterozoic exposures in the Florida Mountains are restricted to a <1 km^2 area on the northwest flank of the range (Clemons, 1998). Rock types include granitic orthogneiss cut by amphibolite dikes. The foliation in the orthogneiss strikes northeast, but variable strikes were also reported (Clemons, 1998). The amphibolite (referred to as hornblende gneiss) has ~50% hornblende, ~30% plagioclase, 15% quartz, and minor potassium feldspar and biotite. The orthogneiss has ^{207}Pb/^{206}Pb zircon dates from 1570 to 1550 Ma (Evans and Clemons, 1988), but these data were from highly discordant zircons.

Burro Mountains

The Burro Mountains have some of the most extensive exposures of Proterozoic rocks in southern New Mexico (Fig. 4), and the entire range has been mapped in detail (Hewitt, 1959; Hedlund, 1978a, 1978b, 1978c, 1978d, 1978e, 1978f, 1978g, 1978h; 1980a, 1980b, 1980c; Finnell, 1987). Paleoproterozoic rocks include deformed igneous rocks and a diverse suite of metasedimentary rocks. These units are intruded by voluminous 1.5–1.4 Ga plutonic rocks and abundant ca. 1.2–1.1 Ga diabase dikes that are beyond the scope of this paper.

The 1.7–1.6 Ga metasedimentary rocks of the region were previously divided into the Ash Creek Formation in the Redrock area (Fig. 3) and Bullard Peak Formation elsewhere in the range (Hewitt, 1959). The rocks in the Ash Creek area near Redrock include greenschist facies calc-silicate rocks, marble, and white-mica schists (Hewitt, 1959; Sanders, 2003). The metasedimentary rocks in the rest of the Burro Mountains are amphibolite grade and rock types include metapelite (biotite-garnet-sillimanite schists), calc-silicate rocks, quartzofeldspathic gneiss, and migmatite (Hedlund, 1980a; Sanders, 2003). The metapelite unit has the largest geographic distribution of the metasedimentary rocks found in the Burro Mountains (Figs. 5A, 5B). This unit is strongly foliated, and the rock texture is schistose to locally gneissic. Mineralogy includes biotite, quartz, microcline, plagioclase, sillimanite, garnet, and retrograde white mica. A mineral stretching lineation is defined by sillimanite.

Igneous rocks of 1.7–1.6 Ga age are less abundant than the metasedimentary rocks and include migmatite, granite gneiss, amphibolite, and gabbro. It is unclear if the protoliths of the quartzofeldspathic gneiss and migmatite are granites or arkosic sandstones. Migmatite has evidence of partial melting, which is displayed in granitic bands parallel to the foliation. This rock has highly variable composition with abundant quartz, feldspar, and biotite, and unlike the metasedimentary rocks, the migmatite samples do not break easily along foliation planes (Fig. 5C). Gneiss with leucogranite protoliths is present but not abundant. These rocks have a strong foliation and consist of quartz, plagioclase, K-feldspar, and biotite (Fig. 5D). Granite gneiss was described as quartzofeldspathic gneiss by previous workers, who considered that some of them might have metasedimentary protoliths (Hedlund, 1980b; Sanders, 2003). Rocks with possible metavolcanic protoliths are also present. These are leucocratic, fine-grained rocks with a weak foliation (Figs. 5E, 5F). Amphibolite is abundant in the Burro Mountains and is associated with exposures of metasedimentary rocks. The amphibolite is generally strongly foliated and locally lineated (Fig. 5G). Mineralogy consists of hornblende and plagioclase. Some samples have as much as 10% quartz and 10% biotite, and may have a sedimentary or volcanic protolith, whereas most are typical amphibolites with protoliths of mafic volcanic rocks or dikes. Gabbro is found as undeformed intrusions in the Redrock area. This unit was previously described as diabase (Hedlund, 1980b; Rämö et al., 2003), but it is coarse grained and significantly different in texture from the 1.2–1.1 Ga diabase dikes that cut all of the Proterozoic units in the range. The gabbro was dated as 1633 ± 5 Ma by U-Pb dating of individual zircons (Rämö et al., 2003).

Metasedimentary rocks in the contact aureole of the 1.63 Ga gabbro in the Burro Mountains have textures indicating static recrystallization. These static textures are recorded by porphyroblasts with muscovite compositions and grow over an earlier foliation defined by white mica and flattened quartz. It is possible that the porphyroblasts may have recrystallized during younger regional reheating, but because these textures are only found adjacent to the mafic intrusion, it strongly suggests that whatever the original phase may have been, it grew statically during 1.63 Ga contact metamorphism.

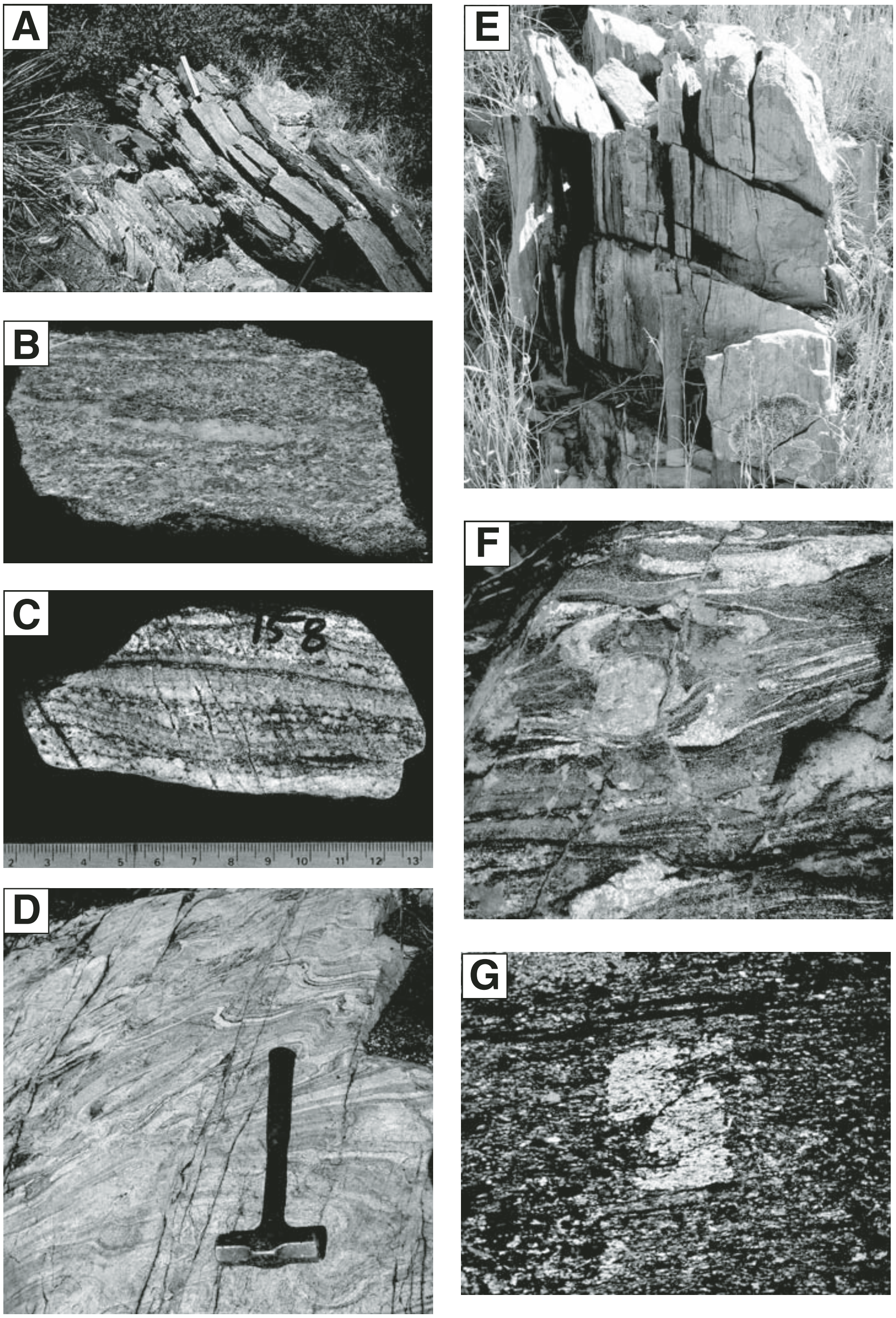

Figure 5. Outcrop and hand-sample photographs from various 1.7–1.6 Ga rocks in the Burro Mountains. (A) Outcrop of foliated metapelitic schist. (B) Hand sample of metapelitic schist. (C) Hand sample of quartzofeldspathic gneiss; sample is 20 cm long. (D) Folded orthogneiss. Hammer is 40 cm long. (E) Outcrop where sample 01BM-110 was collected. Weak foliation and felsic composition suggests that this sample may be a metarhyolite. (F) Strongly foliated amphibolite with folded quartz-rich layers. Heterogeneous layering is evidence that this rock may have a metasedimentary protolith; width of photo is 50 cm. (G) Photomicrograph of white mica porphyroblasts from a quartz-mica schist in the contact aureole of the 1.63 Ga gabbro. Static growth over an existing foliation indicates that deformation had ceased by 1.63 Ga. Porphyroblast is 0.5 mm wide.

STRUCTURAL GEOLOGY

A full treatment of the structures recorded in the pre–1.5 Ga rocks of southern New Mexico is beyond the scope of this paper. Multiple

TABLE 2. MAJOR ELEMENT GEOCHEMISTRY

Sample Rock type	05BM-174 amphibolite	03BM-117 migmatite	05BM-158 migmatite	SA-2 orthogneiss	DMC-1a foliated granite	04BM-137 orthogneiss
SiO_2	50.53	62.76	74.43	77.57	77.79	78.02
TiO_2	1.46	0.96	0.29	0.17	0.1	0.15
Al_2O_3	15.93	18.13	12.77	11.42	11.81	11.39
FeO*	11.5	6.84	1.86	1.03	1.15	1.35
MnO	0.19	0.1	0.05	0.01	0.01	0.01
MgO	6.3	1.7	0.6	0.08	0.15	0.03
CaO	8.87	1.84	0.95	0.13	0.25	0.39
Na_2O	2.98	2.32	2.69	2.79	3.03	2.72
K_2O	0.69	3.34	4.71	5.71	5.08	5.15
P_2O_5	0.15	0.2	0.05	0.04	0.02	0.02
Sum	98.6	98.17	98.42	98.97	99.38	99.24
A/CNK	n/a	1.68	1.13	1.04	1.08	1.06

Notes: All values are in weight %. Data were collected by X-ray fluorescence at the Washington State University GeoAnalytical Laboratory. A/CNK = molar Al_2O_3/(CaO + Na2O + K_2O).

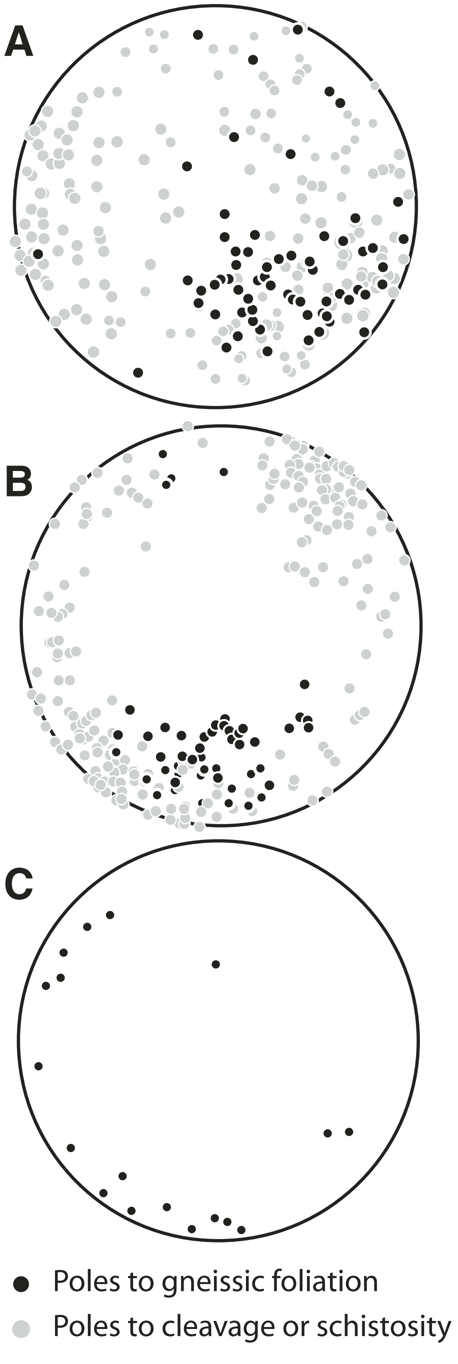

Figure 6. Equal-area stereonets showing the poles to foliations and cleavage. (A) Burro Mountains (Sanders, 2003; Boullion, 2006). (B) San Andres Mountains (Roths, 1991; Serna, 2006). (C) Florida Mountains (Clemons, 1998). Gneissic foliation is from orthogneiss or quartzofeldspathic gneiss, whereas cleavage and/or schistosity data are from metasedimentary rocks.

post-Mazatzal orogeny deformational events, which have modified the original characteristics of foliations, lineations, and folds, have occurred in the region. These include unknown deformation associated with the Mesoproterozoic Grenville orogeny, Jurassic rifting, and more recent events such as Laramide (Late Cretaceous–Paleogene) shortening and a history of late Paleogene–Neogene extension related to both Basin and Range deformation and rifting along the Rio Grande corridor (Mack, 2004; Seager, 2004).

Several studies have measured gneissic foliations in metaplutonic rocks and the foliations associated with cleavage or schistosity in metasedimentary rocks (Alford, 1987; Roths, 1991; Vollbrecht, 1997; Clemons, 1998; Boullion, 2006; Serna, 2006). These are divided into metasedimentary and gneissic categories and plotted on stereonets, but the data are plotted in their current orientation and not corrected for younger tilting (Fig. 6). Phanerozoic deformation would not change the relative orientations of the structures within each domain within one mountain range, but it likely precludes direct comparison of attitudes between ranges. It is clear that even within one mountain range, there is a wide range of foliation attitudes, but in general foliations are steeply dipping. In both the Burro Mountains and San Andres Mountains, gneissic foliation in quartzofeldspathic gneiss and granite gneiss is similar to the schistosity in adjacent metapelitic units. In the Burro Mountains, the majority of the foliations strike between ~N45W and N45E, and dips are >70°. In the San Andres range, most attitudes strike northwest with steep dips. The orthogneiss in the Florida Mountains has both northeast- and northwest-striking foliations that dip >70°. In the San Andres Mountains, boudins of amphibolite within granitic orthogneiss have axes trending nearly east-west with shallow plunges.

Studies of ca. 1.4 Ga igneous rocks in southwestern New Mexico (Amato et al., 2006) indicate that the oldest rocks dated as part of this magmatic event are 1.46 Ga and do not contain a pervasive, consistent fabric such as the one recorded in the granite gneiss and metapelitic schist of southern New Mexico. These intrusions heated the area to temperatures sufficient to reset the $^{40}Ar/^{39}Ar$ system in hornblende from amphibolite (Amato et al., 2006).

GEOCHEMISTRY RESULTS

Several of the ca. 1.6 Ga igneous rocks were analyzed for major (Table 2) and trace element geochemistry (GSA Data Repository Table DR1[1]). The analytical techniques can be found in the Data Repository. Samples SA-2, 04BM-137, and 05BM-158 are weakly peraluminous granitic gneisses from the San Andres and Burro Mountains according to the alkali ratios (A/CNK), based on the molar concentrations of $Al_2O_3/(K_2O + Na_2O + CaO)$. They have SiO_2 concentrations ranging from 74.4 to 78.0 wt%, <0.3% TiO_2, <0.7% MgO, total Fe as FeO (FeO*) between 1%–2%, and K_2O between 4.7% and 5.7%. The chondrite-normalized rare earth element (REE) plot for sample SA-2 shows a light REE-enriched pattern, with a slope defined by a normalized ratio of La/Lu of ~13, and a strong negative Eu anomaly characterized by a Eu/Eu* ratio of 0.26 (Fig. 7). Sample 04BM-137 has elevated light REE concentrations, a positive Ce anomaly, a negative Eu anomaly with Eu/Eu* = 0.65, and increasing concentrations of heavy REE with increasing atomic number.

Sample DMC-1a is a foliated granite, not a gneiss, but shares geochemical characteristics

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[1] GSA Data Repository Item 2007262, Analytical techniques, complete geochemical and geochronological data sets, and summary of data sources for Figure 13, is available at www.geosociety.org/pubs/ft2007.htm. Requests may also be sent to editing@geosociety.org.

with these other rocks, such as SiO_2 of 77.8%, K_2O of 5.1%, and FeO* of 1.2%. The REE pattern is enriched in the light REEs and it has the highest concentrations of heavy REEs and the strongest negative Eu anomaly at Eu/Eu* = 0.07. A chondrite-normalized trace element spidergram shows that the gneisses have enriched concentrations of large-ion lithophile elements (LILE) such as Rb, Th, and K, and they have low concentrations of Nb and Ta (Fig. 8).

Sample 03BM-117 is a strongly peraluminous migmatite, based on an A/CNK ratio of 1.68, with a possible sedimentary protolith. It has 62.8 wt% SiO_2, ~7% total FeO*, and Al_2O_3 of 18%. It has a light REE–enriched chondrite-normalized pattern with La/Lu = 6.1, a negative Eu anomaly with Eu/Eu* = 0.60, and relatively flat pattern for the heavy REEs. The concentrations of light REEs are nearly as high as those from samples 05BM-158, SA-2, and DMC-1a.

The amphibolite, sample 05BM-174, has a basaltic protolith composition, with SiO_2 of 51% and K_2O of 0.7%. MgO is 6.3% and FeO* is 11.5%. The REE pattern is slightly enriched in the light REEs with chondrite-normalized La/Lu of 2.1. This sample does not have a Eu anomaly, and it has lower concentrations of LILE and fairly low Nb and Ta relative to K and La (Fig. 8).

GEOCHRONOLOGICAL RESULTS

U-Pb geochronology was carried out using two methods. Sensitive high-resolution ion microprobe (reverse geometry) (SHRIMP-RG) dating was conducted at the Stanford–U.S. Geological Survey Ion Probe Facility. Laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) dating was conducted on both igneous and metasedimentary rocks at the University of Arizona. (For a discussion of the analytical techniques and data reduction procedures, see footnote 1.) A summary of the ages obtained is reported in Table 3. All uncertainties are reported in the text at the 2σ level. Complete results are listed in Tables DR2, DR3, and DR4 (see footnote 1).

1680–1650 Ma Igneous Rocks

The granite gneisses dated include sample 04BM-137 from the Burro Mountains, samples SA-2C and SA-2 from the San Andres Mountains, and sample 01FM-3 from the Florida Mountains (Fig. 9).

Sample 04BM-137 is a foliated and recrystallized leucocratic granite or migmatite with <5% biotite. Zircon grains were analyzed by LA-MC-ICPMS with a beam size of 35 µm. Zircons are euhedral with aspect ratios of 2:1–3:1 and

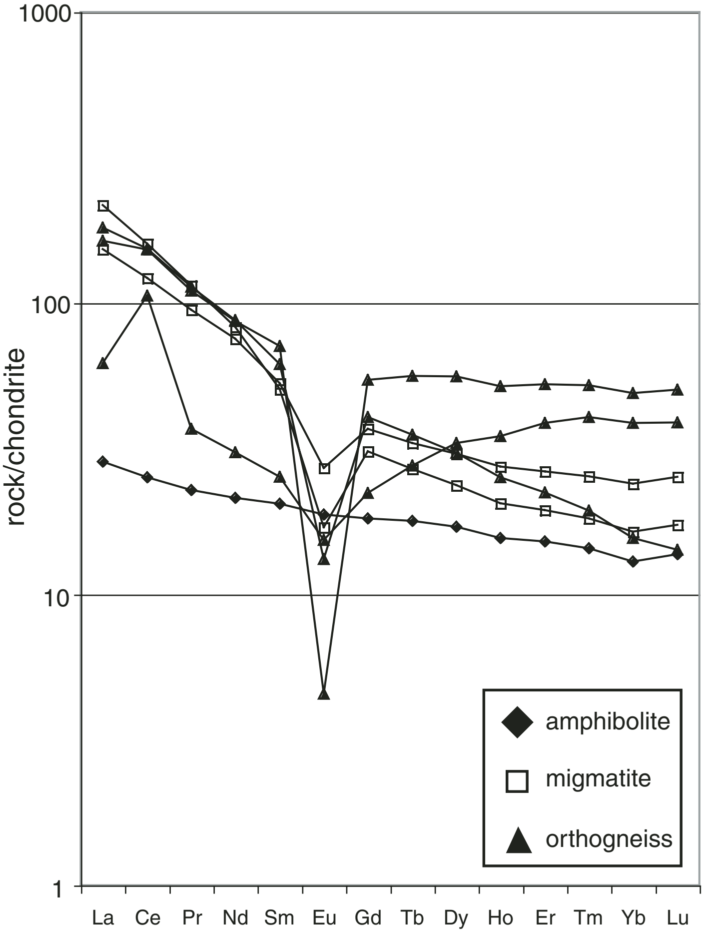

Figure 7. Chondrite-normalized rare earth element plots of some of the studied Proterozoic samples. Normalization factors are from Anders and Grevesse (1989).

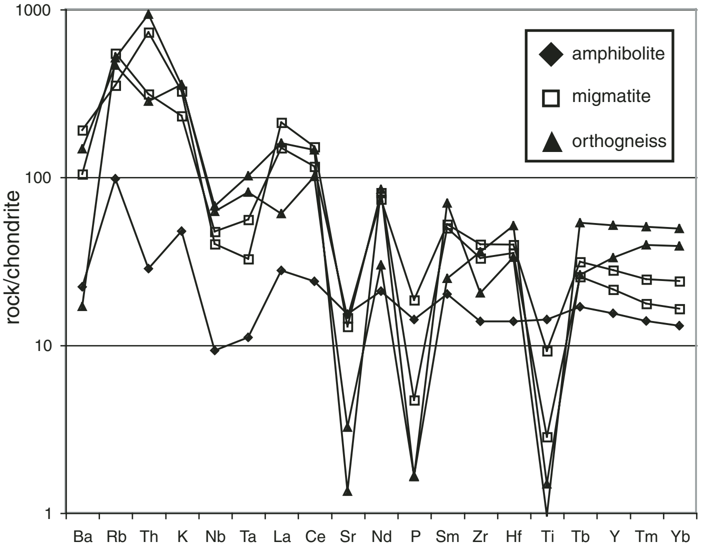

Figure 8. Chondrite-normalized trace element spidergram of some of the studied Proterozoic samples. Chondrite values are from Thompson (1982).

TABLE 3. SUMMARY OF U-PB ZIRCON GEOCHRONOLOGIC RESULTS

Sample	Rock type	Area	Age (Ma)	± 2σ (Ma)	MSWD	n	Technique
03BM-110	Metavolcanic	Burro Mountains, NM	1633	8	1.4	17	SHRIMP
04BM-137	Migmatite	Burro Mountains, NM	1676	17	2.0	47	LA-MC-ICPMS
01FM-3	Gneiss	Florida Mountains	1652	33	1.2	41	LA-MC-ICPMS
03SA-2c	Gneiss cores	San Andres Mountains, NM	1674	26	1.6	4	SHRIMP
03SA-2c	Gneiss rims	San Andres Mountains, NM	1617	11	1.6	11	SHRIMP
DMC-1	Foliated granite	San Andres Mountains, NM	1631	21	1.3	6	SHRIMP
SA-2	Felsic gneiss	San Andres Mountains, NM	1649	13	1.5	8	SHRIMP

Notes: For complete data sets see GSA Data Repository Tables DR2, DR3, and DR4 (see footnote 1). MSWD—mean square of weighted deviates; SHRIMP—sensitive high-resolution ion microprobe; LA-MC-ICPMS—laser ablation–inductively coupled plasma mass spectrometry.

lengths ranging from 100 to 300 μm. Cathodoluminescence (CL) imaging of these grains shows that most of them have oscillatory zonation. A few grains appear to have low-U cores. Of the 48 analytical spots, all but one had ^{238}U/^{206}Pb spot ages that were within +5% and –30% of the ^{207}Pb/^{206}Pb ages. Th/U ratios range from 0.2 to 1.3. The weighted mean of all ^{207}Pb/^{206}Pb ages is 1676 ± 11 Ma with a mean square of weighted deviates (MSWD) of 2.0. Inclusion of systematic errors yields an interpreted crystallization age of 1676 ± 17 Ma. A few ^{207}Pb/^{206}Pb ages from this sample are older than 1700 Ma, but these are generally discordant and their age minus the uncertainty overlaps with an age at or younger than 1680 Ma (Fig. 9). The tip and core zircon ages overlap within 2σ uncertainty. Sample 05BM-158, a granitic gneiss–migmatite from the Burro Mountains, has a preliminary age of 1640 ± 40 Ma, but complexities in the zircon ages owing to Pb loss and metamorphism need to be resolved. We are confident, however, that the sample is essentially similar to the other deformed Burro Mountains granitic rocks.

Samples SA-2 and 03SA-2c are granite gneisses from San Nicolas Canyon (Fig. 3) collected from the same general area as a sample previously dated as 1730 ± 130 Ma (Roths, 1991). The dated samples have 5%–10% biotite and a strong macroscopic foliation. Sample 03SA-2c is cut by a boudinaged amphibolite and is also cut by small dikes probably of the ca. 1.45 Ga Mineral Hill granite. Zircons from sample SA-2C were analyzed by SHRIMP. The grains are 75–150 μm in length and have aspect ratios of 2:1–3:1. Although some of the grains are euhedral, many are subhedral to rounded. CL images show concentric zonation and a difference in CL intensity between the cores and rims. The rims have a brighter CL intensity, indicating lower U concentrations. Two groups of ^{207}Pb/^{206}Pb ages are found in the 15 grains analyzed. The oldest ages are from the cores of zircons and four grains yielded a weighted mean ^{207}Pb/^{206}Pb age of 1674 ± 26 Ma (MSWD = 1.6). These grains all have Th/U of 0.5. The younger age group is discussed in the next section.

Zircons from sample SA-2 were also analyzed by SHRIMP. The grains are 100–150 μm in length and have aspect ratios of 2:1–3:1. There are two populations of zircon grains. Some are euhedral to subhedral, have concentric zonation, and brighter CL rims and no evidence of inherited cores. The other population has high U, extreme discordance, and mottled, irregular CL patterns suggestive of hydrothermal alteration. All of the zircons ages reported are from the unaltered population. CL images show concentric zonation and no evidence of inherited cores. In the eight grains analyzed, Th/U ranges from 0.3 to 0.5 with U concentrations ranging from 500 to 900 ppm. One grain has a core age of 1645 ± 10 Ma and a rim age of 1612 ± 23 Ma. The weighted mean of all eight of the ^{207}Pb/^{206}Pb ages is 1649 ± 13 Ma (MSWD = 1.5).

The Florida Mountains sample, 01FM-3, is a recrystallized, strongly foliated biotite granite orthogneiss. Zircons were analyzed by LA-MC-ICPMS during two separate sessions with variable beam size (15 μm and 50 μm), resulting in different levels of precision on individual spot analyses. The zircons are euhedral and range from 200 to 250 μm in length with aspect ratios ranging from 2:1 to 5:1. Many grains have small inclusions. Th/U is generally high (0.5–1.5) and U concentrations average ~75 ppm. The ^{207}Pb/^{206}Pb ages range from ca. 1800 to 1580 Ma, but a weighted mean of the largest population of 41 grains yields an age of 1652 ± 33 Ma with inclusion of systematic errors (MSWD = 1.2). The upper intercept age on a concordia diagram is 1671 ± 26 Ma (MSWD = 2.6). Most of the ages older than1700 Ma are discordant or have high uncertainties.

1630–1615 Ma Igneous Rocks

Sample DMC-1a is from a weakly foliated coarse-grained granite pluton in Dead Man Canyon. It consists of potassium feldspar megacrysts as long as 2 cm, plagioclase, quartz, and ~15% biotite. A sample from this unit was previously dated as 1632 ± 24 Ma (Roths, 1991). Previous workers noted that the rock was foliated, but our work indicates that the foliation is likely a flow fabric because it is variable in intensity and potassium feldspar megacrysts do not align with the foliation defined by biotite. Eight zircons were analyzed by SHRIMP (Fig. 10) and all have Th/U between 0.4 and 0.7. Grains are euhedral, 100–200 μm long, and have aspect ratios ranging from 2:1 to 8:1. Zonation is oscillatory and most grains have a thin, low CL (high U) rim. One analysis is >30% discordant and has a >5% uncertainty, and another has an anomalously young ^{207}Pb/^{206}Pb age. If all of the concordant data (six analyses) are considered, the weighted mean ^{207}Pb/^{206}Pb age is 1631 ± 24 Ma (MSWD = 2.1). The younger ages from sample SA-2C are mainly from the rims of the zircon grains. These rims generally have lower Th/U (<0.5), and together 11 analyses yield a weighted mean age of 1617 ± 11 Ma (MSWD = 1.6).

Sample 03BM-110 is a weakly foliated, fine-grained leucocratic rock with a possible metavolcanic protolith. Zircons were analyzed by SHRIMP and are euhedral with concentric zonation. They are 100–200 μm in length with aspect ratios of 2:1–3:1. Th/U ranges from 0.4 to 0.7, and one of the analyzed grains has high U and is highly discordant. The weighted mean ^{207}Pb/^{206}Pb age of the remaining 17 analyses is 1633 ± 8 Ma (MSWD = 1.4).

Detrital Zircon Ages from Metasedimentary Rocks

Detrital zircons from four samples from the Burro and San Andres Mountains were analyzed by LA-MC-ICPMS (Fig. 11; Table DR4 [see footnote 1]). Peaks on relative probability distribution diagrams (Ludwig, 2003) are considered significant if they consist of three or more ages. All uncertainties listed are at the 2σ level and include both random and systematic errors.

Sample 01BM-09 is a strongly foliated metapelitic schist with biotite, garnet, and sillimanite with some younger overgrowths of white mica. We analyzed 48 zircons from this sample and all but two were >70% concordant. The ^{207}Pb/^{206}Pb data include one Archean age at 2878 Ma, which is the only Archean grain found in this study, and all of the other ages are between 1851 and 1655 Ma. The youngest peak on a relative probability distribution diagram is at 1715 Ma and consists of 19 grains. The most significant peak is at 1762 Ma. The U-Pb dating of detrital zircons from other samples from the high-grade metasedimentary rocks in the Burro Mountains was unsuccessful owing to the intensity of metamorphic growth during ca. 1.4 Ga heating.

The other two samples were from lower grade samples from the Redrock area near the 1.63 Ga

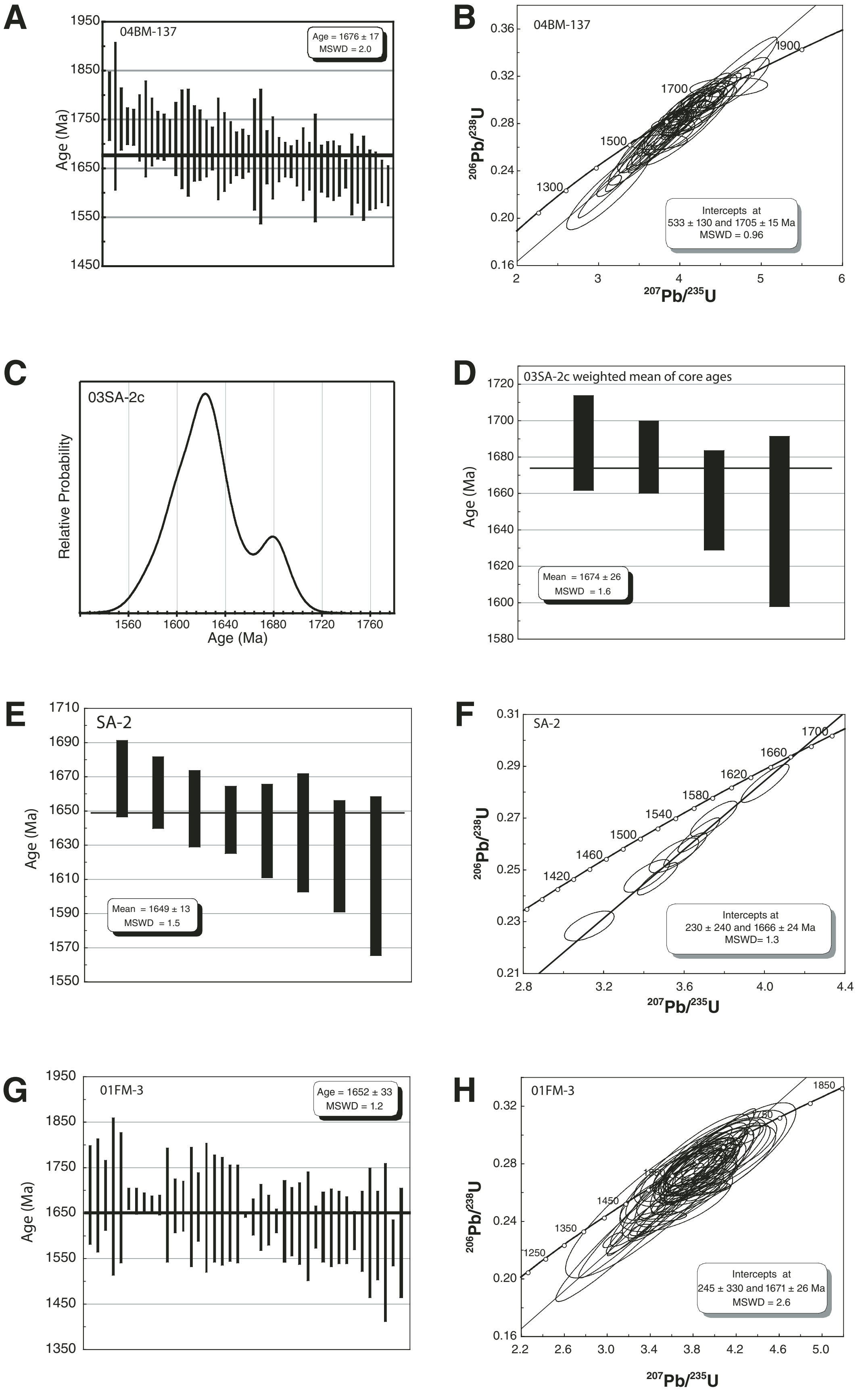

Figure 9. U-Pb zircon geochronology plots for rocks ranging in age from 1680 to 1650 Ma. All weighted mean plots here and in Figure 13 show individual data points plotted at the 2σ level, and all quoted ages are at the 2σ level. Plots were created using Isoplot (Ludwig, 2003). (A) Weighted mean of $^{207}Pb/^{206}Pb$ ages from Burro Mountains granitic orthogneiss 04BM-137 is 1676 ± 17 Ma (n = 47). Error includes both random and systematic errors. (B) Concordia diagram from the same data set for sample 04BM-137 omitting two analyses with U-Pb uncertainties of >10%. Upper intercept age is 1705 Ma. If concordia is anchored to 0 age the upper intercept is 1675 ± 12 Ma. (C) Relative probability diagram of $^{207}Pb/^{206}Pb$ ages from San Andres Mountains gneiss sample 03SA-2c indicates two populations, and cathodoluminescence imaging suggests different growth histories between the cores and rims of the zircons. (D) Weighted mean of $^{207}Pb/^{206}Pb$ ages from four core analyses from this sample is 1674 ± 26 Ma (mean square of weighted deviates, MSWD = 1.6). Rim age analyses are shown in Figure 13. (E) Weighted mean of eight $^{207}Pb/^{206}Pb$ ages from San Andres Mountains gneiss sample SA-2 is 1649 ± 13 Ma. (F) Concordia diagram of the same data set from sample SA-2. Upper intercept is 1666 ± 24 Ma. (G) Weighted mean of $^{207}Pb/^{206}Pb$ ages from Florida Mountains gneiss sample 01FM-3 is 1652 ± 33 Ma (n = 56). Disparity in uncertainties is from different beam size during two analytical sessions. (H) Concordia diagram of same data set from sample 01FM-3, omitting one analysis with U/Pb uncertainty>10%.

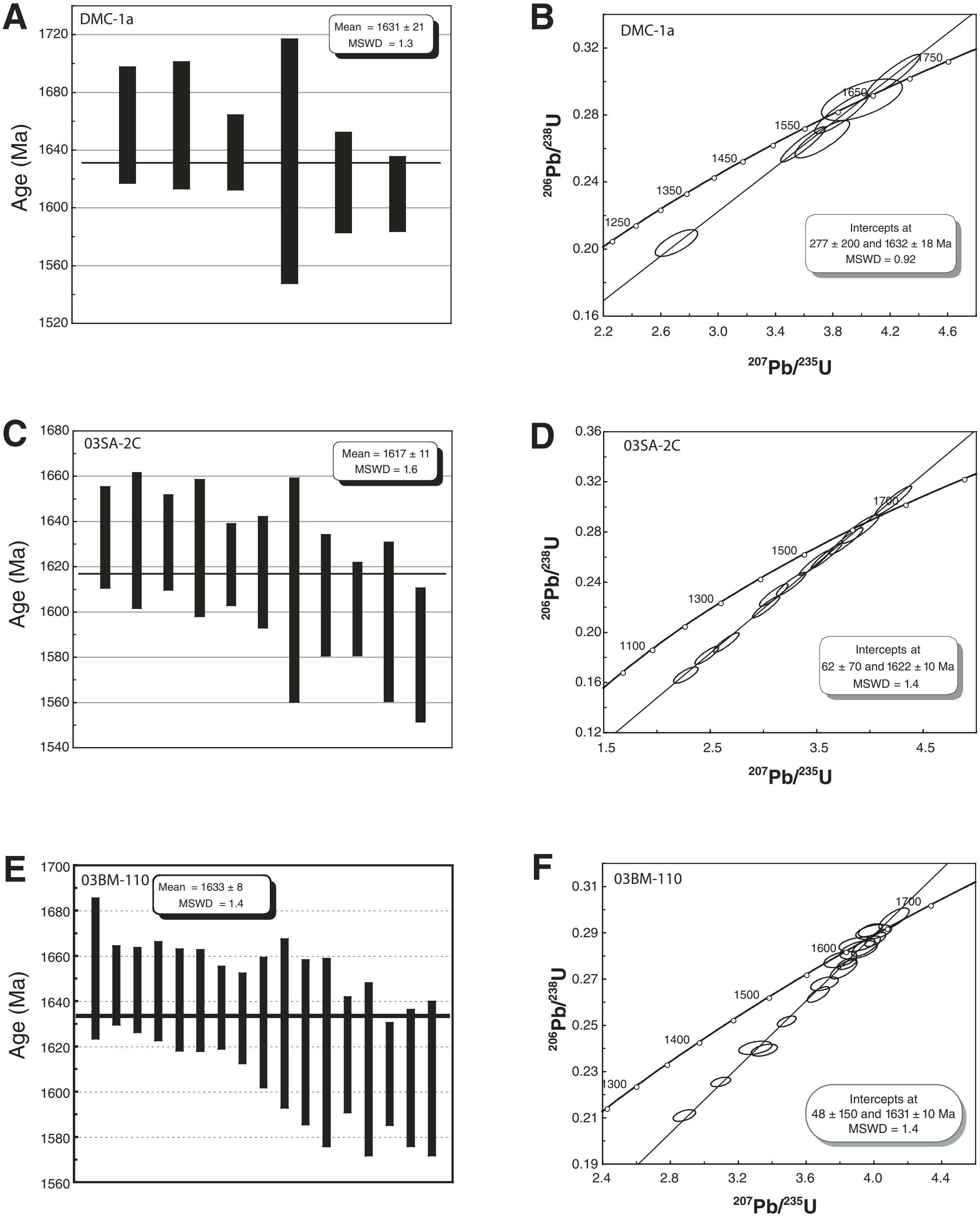

Figure 10. U-Pb geochronology for 1630–1615 Ma rocks. (A) Sample DMC-1a, a foliated granite from the San Andres Mountains, has a weighted mean $^{207}Pb/^{206}Pb$ age of 1631 ± 21 Ma and (B) an upper intercept on concordia age of 1632 ± 18 Ma. (C) Weighted mean of $^{207}Pb/^{206}Pb$ ages from San Andres Mountains gneiss sample 03SA-2C rim analyses is 1617 ± 11 Ma, and (D) upper concordia intercept of these data is 1622 ± 10 Ma. See Figure 12 for core analyses. (E) Sample interpreted as a metavolcanic rock 03BM-110 from the Burro Mountains has a weighed mean $^{207}Pb/^{206}Pb$ age of 1633 ± 8 Ma, and (F) upper concordia intercept of these data is 1631 ± 10 Ma. MSWD—mean square of weighted deviates

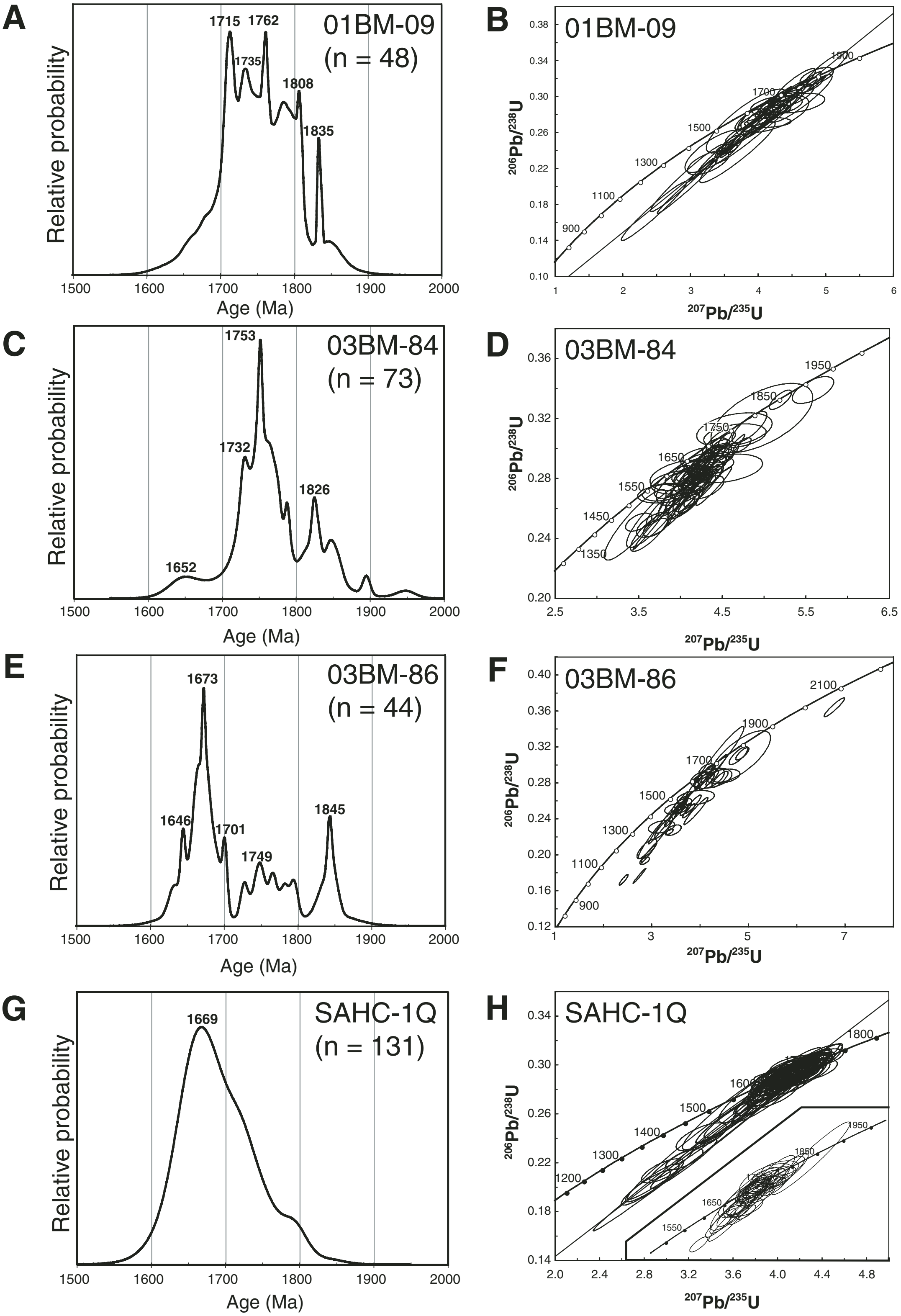

Figure 11. Relative probability diagrams for $^{207}Pb/^{206}Pb$ ages and U-Pb concordia diagrams from detrital zircons in Proterozoic metasedimentary rocks. (A) Burro Mountains sample 01BM-09 is a metapelitic schist (n = 48). (B) Concordia diagram from 01BM-09. (C) Burro Mountains sample 03BM-84 is a quartzite (n = 73). (D) Concordia diagram for sample 03BM-84. (E) Burro Mountains sample 03BM-86 is a spotted hornfels (n = 44). (F) Concordia diagram for sample 03BM-86. (G) San Andres Mountains sample SAHC-1Q is a quartzite (n = 131). (H) Concordia diagram for youngest 91 grains from sample SAHC-1Q that make up the peak; inset shows oldest 40 grains from same sample.

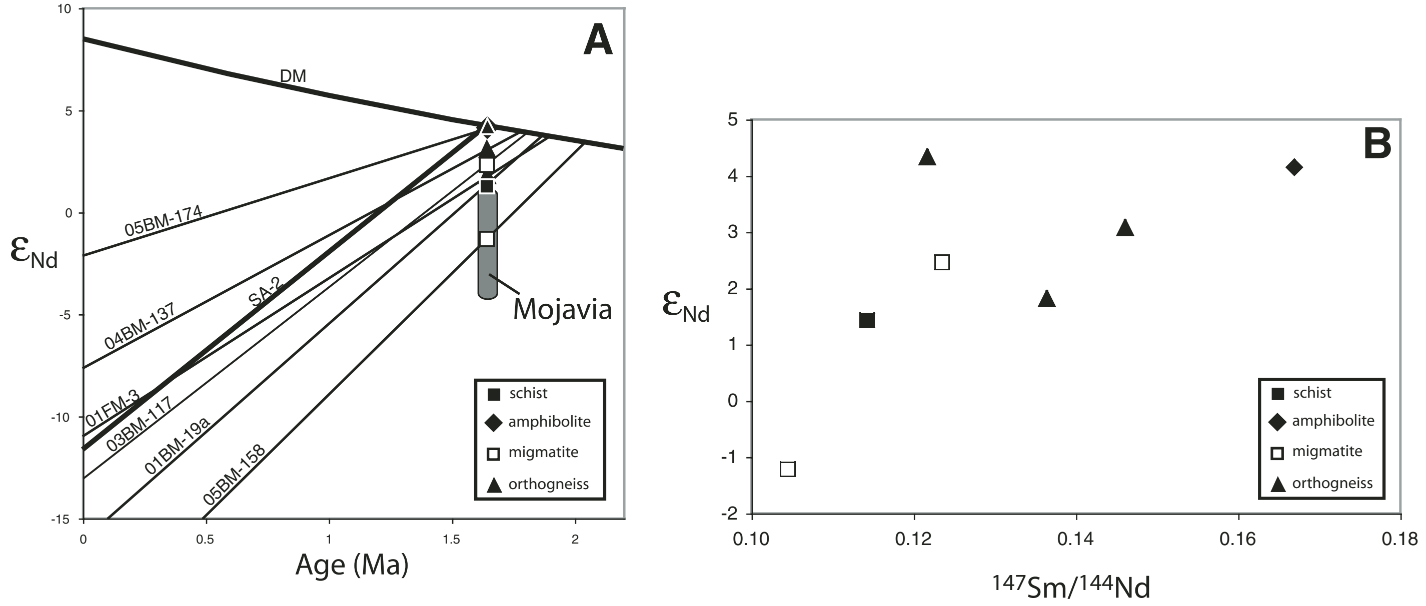

Figure 12. (A) Nd isotope evolution diagram. Samples 05BM-174 and SA-2 both have model ages equal to their formation age. The other igneous and metasedimentary rocks have model ages older than their formation or depositional ages. DM is the depleted mantle evolution curve (DePaolo, 1981). Gray area labeled Mojavia is the range of ε_{Nd}(t) values reported from the Mojave province (Bennett and DePaolo, 1987) recalculated for 1650 Ma. All but one of the values from this study have a higher ε_{Nd}(t) than the Mojave province rocks.

gabbro. The protoliths for these samples were less pelitic and more quartzose than the protolith for sample 01BM-09. They have textures attributed to contact metamorphism in the aureole of the 1.63 Ga gabbro. Sample 03BM-84 is a quartzite with sprays of white mica and chlorite growing at random orientations. A total of 73 grains analyzed from this sample were subrounded to rounded and range in size from 90 to 130 μm. All are >80% concordant. The $^{207}Pb/^{206}Pb$ ages range from 1949 to 1637 Ma and the youngest peak on a relative probability distribution diagram is 1652 Ma. The most significant peak is at 1753 Ma.

Sample 03BM-86 is a spotted hornfels with abundant quartz and multiple generations of white mica. Zircon grains separated from this sample are not well rounded, and some are euhedral to subhedral. Grain sizes range from 100 to 150 μm. The $^{207}Pb/^{206}Pb$ ages range from 2164 to 1632 Ma. The youngest $^{207}Pb/^{206}Pb$ age peak on the probability distribution diagram is at 1646 Ma and the most significant peak is at 1673 Ma.

Sample SAHC-1Q is a metamorphosed lithic quartzite from Hembrillo Canyon in the San Andres Mountains. Rounded quartz grains are surrounded by a matrix of recrystallized lithic grains containing white mica and displaying a weak foliation. Quartz grains are as large as 5 mm across, and graded bedding is present. There were 132 zircons analyzed from this sample using LA-MC-ICPMS. More than 100 of these grains were >90% concordant. Th/U ranges from 0.1 to 1.2, with >90% of the grains having Th/U > 0.3. A probability distribution diagram has only one $^{207}Pb/^{206}Pb$ age peak at 1669 Ma consisting of 91 grains. The older ages range up to 1842 Ma but do not form a distinct peak.

Nd ISOTOPIC RESULTS

The Nd isotopic composition was measured on seven samples (Fig. 12; Table 4). See the Data Repository (see footnote 1) and Farmer et al. (1991) for a discussion of the analytical techniques. All ε_{Nd}(t) values were calculated for an age of 1650 Ma. Sample 01BM-19a is a metapelitic schist that has an ε_{Nd}(t) initial value of +1.4. Sample 03BM-117 is a migmatite with a possible sedimentary protolith and has ε_{Nd}(t) of +2.5. Deformed granitic samples have ε_{Nd}(t) initial values that range from +4.3 to –1.2. Sample 05BM-174, the amphibolite from the Burro Mountains, has ε_{Nd}(t) of +4.2. Depleted mantle model ages (DePaolo, 1981) for samples 05BM-174, the amphibolite, and SA-2, the granitic gneiss, are similar to their crystallization ages, suggesting they are dominantly juvenile melts (Fig. 9). The other samples have model ages ranging from 1780 to 2000 Ma, suggesting that

TABLE 4. Nd ISOTOPE DATA

Sample		Concentration		Atomic ratio	Measured ratio†	$\varepsilon_{Nd}(t)$ ‡
	SiO_2 (wt%)	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	
01BM-19a	n/a	8.07	42.7	0.1142	0.511816 ± 5	1.4
03BM-117	62.8	8.67	42.5	0.1234	0.511969 ± 14	2.5
05BM-158	74.4	9.65	55.9	0.1044	0.511575 ± 7	-1.2
05BM-174	50.5	3.9	14.1	0.1669	0.512527 ± 9	4.2
04BM-137	78.0	5.92	24.5	0.1461	0.512246 ± 9	3.1
03SA-2	77.6	11.3	56.4	0.1217	0.512045 ± 7	4.3
01FM-3	n/a	6.89	30.5	0.1364	0.512077 ± 7	1.8

Notes: Values used for chondritic uniform reservoir (CHUR) are $^{143}Nd/^{144}Nd$ = 0.512638, $^{147}Sm/^{144}Nd$ = 0.1967. Decay constants are ^{147}Sm, 6.54E-12 yr^{-1}.
Isotope dilution concentration determinations accurate to 0.5% for Sm and Nd.
Total procedural blank averaged 100 pg for Nd during study period.
Measurements (n = 33) of the La Jolla Nd standard yielded $^{143}Nd/^{144}Nd$ =0.511838 ± 8 (2 mean).
†All errors in measured isotopic ratios are at the 95% confidence limit.
Corrected for mass fractionation by normalizing to $^{146}Nd/^{144}Nd$ = 0.72190.
‡ε_{Nd}(t)= {[$^{143}Nd/^{144}Nd$(T)sample/$^{143}Nd/^{144}Nd$(T)CHUR] – 1} × 10,000. Calculated at 1650 Ma.

variable amounts of older crust were involved in their formation.

DISCUSSION

Our new data on the chemistry and age of Proterozoic rocks from southern New Mexico can be combined with the existing data set from Arizona and northern New Mexico to assess the age and origin of Mazatzal province crust, subdivisions of the Mazatzal province, and the timing of onset and duration of the Mazatzal orogeny.

Age of the Paleoproterozoic Crust

The geochronological results presented here are consistent with a lack of pre-1.7 Ga rocks in the Mazatzal province in New Mexico. The ages of these deformed felsic igneous rocks range from ca. 1675 to 1650 Ma. The oldest deformed igneous rocks in this study are plutons dated as 1676 ± 17 Ma (Burro Mountains), 1674 ± 26 Ma from the cores of zircons from the San Andres Mountains orthogneiss, and 1652 ± 33 Ma (Florida Mountains). The sample from the San Andres Mountains had a previously reported age of 1730 ± 130 Ma (Roths, 1991), but our new data indicate an age of 1649 ± 13 Ma. Pre-1.7 Ga rocks have still not yet been found in southern New Mexico. The protolith age for the amphibolite (sample 05BM-174) is unknown, but it shares a deformational fabric with the granite gneisses and is likely coeval. Other previously published dates on igneous rocks in southern New Mexico range from 1655 to 1630 Ma (Table DR5; see footnote 1).

Some workers emphasize that there is some pre-1.8 Ga material in the Yavapai province, and that this indicates the presence of Trans-Hudson–Penokean-age crust in southern Laurentia (Bickford and Hill, 2007). In this regard, we note that no clearly inherited zircons or inherited cores were observed in any of the 1.68–1.65 Ga intrusive rocks in this study.

Crustal Evolution and Tectonic Setting of Magmatism

The main goals of the geochemical study were to (1) determine if these igneous rocks represent juvenile additions to the crust and (2) evaluate the tectonic setting of 1680–1650 Ma granitic intrusions and nearly coeval sedimentary rocks in southern New Mexico. The Nd isotope data do not yield direct constraints regarding the tectonic environment in which the basement gneisses in southern New Mexico formed. The geochemical data set from southern New Mexico remains sparse, and even with our new data, it is not possible to create a complete detailed petrogenetic model. Nevertheless, the trace element and Nd isotopic data serve to characterize these rocks and can be used for comparisons with other rocks in the Mazatzal province. The igneous rocks from this study have undergone multiple episodes of high-temperature metamorphism and deformation. This likely affected the concentrations of some major elements and trace elements such as Rb, Ba, and Sr (MacLean, 1990). The REEs and high field strength elements such as Zr, Hf, Nb, Ta, and Y are thought to be not as mobile during postemplacement heating and strain (Pearce and Cann, 1973; Wood, 1980; MacLean, 1990; Ruks et al., 2006). Most of our interpretations rely on REE, Nb, and Ta concentrations, and the Nd isotopic composition of the rocks.

The high $\varepsilon_{Nd}(t)$ values determined for the majority of the felsic gneisses and granitic rocks analyzed (1.8–4.3) from southern New Mexico are typical of Mazatzal province basement rocks (Bennett and DePaolo, 1987; Reed et al., 1993) and suggest that these rocks represent continental crust formed from partial melting of the upper mantle at or near the time at which their igneous protoliths crystallized (Fig. 9). There is no evidence from the gneiss Nd isotope data zircon U-Pb ages for the incorporation of Trans Hudson age or older crustal material, and so we agree with earlier workers that the Mazatzal province represents juvenile continental crust shielded from interaction with older crust during its formation. We cannot, however, exclude the possibility that either Mazatzal orthogneisses or paragneisses in southern New Mexico contain a some proportion of Yavapai province crust, or sediment derived thereof, given the small isotopic contrast that would have existed between existing Yavapai crust and crust newly formed ca. 1.65 Ma.

All of the samples have highly evolved with SiO_2 concentrations of ~75%, with the exception of the amphibolite (Table 2). The lack of abundant intermediate compositions is relatively atypical of an arc setting, but this may be the result of selective preservation: the current proportions of mafic, intermediate, and felsic rocks may not reflect the original proportions in the region. Felsic rocks are commonly found in arc settings, even in island arcs such as the Talkeetna arc (e.g., Johnsen et al., 2007), so their presence alone is not sufficient to rule out a subduction origin for these rocks. Trace element geochemistry can be used with caution to assess the tectonic setting of igneous rocks for which other evidence of their origin has been obscured by deformation. Most of the granites from this study have geochemical signatures that are consistent with those found in typical arc magmas (Kelemen et al., 2003). The positive Ce anomaly is unusual and typically occurs in rocks formed in an oxidizing environment. The strong negative Eu anomalies are also typical of evolved magmas, and the magnitude of the Eu anomaly is proportional to the amount of light REE enrichment in the samples. Nearly all of the samples have low Nb and relatively low Ta concentrations relative to the REEs, and this is highly characteristic of arc magmatism (e.g., Kelemen et al., 1993).

The geochemical data provide few additional insights into whether the rocks formed during active arc magmatism, or, as others have suggested based on the relative paucity of preserved, intermediate composition volcanic rocks, as the product of reworking of the continental crust during crustal rifting after stabilization of the continental crust. All we can state is that the trace element abundances of the southern New Mexico orthogneisses and felsic metavolcanic rocks are characterized by high LILE/HFSE (high field strength element) ratios, despite the likelihood that the LILE were mobile during later metamorphic events (Fig. 8), and that such high ratios are characteristic of arc igneous rocks (Keleman et al., 1993). The geochemical data alone cannot readily distinguish between formation from differentiation of a parental arc magma or partial melting of relatively young mafic arc lower crust, but in either case the magmas are fundamentally related to an arc system that was adding juvenile material to the Mazatzal province and resulted in crustal growth along the margin.

Previous studies in northern New Mexico and southeastern Arizona have found that the geochemistry and isotopic composition of igneous rocks from this period are consistent with arc magmatism (Bennett and DePaolo, 1987; Karlstrom and Bowring, 1988; Eisele and Isachsen, 2001; Karlstrom et al., 2004). The samples from this study are coeval with samples interpreted as arc rocks in Arizona and northern New Mexico. The rocks of the Cochise block are generally younger than those from this study, in the range of 1647–1630 Ma, but they are also interpreted as derived from a juvenile volcanic arc (Eisele and Isachsen, 2001). The paucity of ophiolites and preserved accretionary assemblages and the presence of a small number of Trans-Hudson Penokean ages (ca. 1850 Ma) for Paleoproterozoic rocks and inherited zircons within southern Laurentia in this region were noted to be inconsistent with an arc model (Bickford and Hill, 2007). We did not observe any older inherited zircons in the rocks from this study, and the Nd isotopic composition of the samples is not consistent with the incorporation of significantly older crust into the melts.

Age and Source of Sedimentary Rocks

The depositional age of metasedimentary rocks is constrained by the age of the youngest, multigrain ($n > 2$) zircon age population in each sample analyzed by LA-MC-ICMPS. In the San Andres Mountains, the youngest (and largest) population has an age of 1669 Ma. In the Redrock area of the Burro Mountains, the youngest populations were 1652 Ma and 1646 Ma in two samples, and in the main part of the Burro Mountains the youngest grains in one sample were 1715 Ma. Both of the Redrock area samples have zircons with ages typical of the Mazatzal and Yavapai provinces, whereas the sample from the main area of the Burro Mountains has only Yavapai province ages (older than 1700 Ma).

The abundance of zircons with ages typical of the Yavapai province is intriguing given that most models of the Mazatzal province indicate that it originated as a juvenile (oceanic?) arc system. It seems likely that if most of the Mazatzal province rocks are arc related, then it must have been very close to the southern boundary of the Yavapai province at the time of deposition of the sediment, or ca. 1650 Ma based on the youngest age clusters in the Burro Mountains samples. The proximity of the Yavapai province rocks at this time is consistent with the timing of the Mazatzal orogeny that may have begun very close to 1650 Ma. The lack of Archean grains (only 1 grain out of ~300 analyzed) suggests that there were no significant sediment sources from the Wyoming or Mojave provinces either because of low topography or barriers to drainage systems between these areas and the southern Mazatzal province.

Subdivisions of the Mazatzal Province

Previous studies of southern Laurentia divided it into two provinces and seven discrete tectonostratigraphic blocks based on lithology and the age of deformational events (Karlstrom et al., 1987, 1990; Karlstrom and Bowring, 1988, 1993). The Mazatzal province was subdivided into the Mazatzal, Sunflower, and Pinal blocks, all of which underwent deformation between 1.7 and 1.6 Ga. The Mazatzal block was different from the rest of the Mazatzal province in that it contained rocks older than 1.7 Ga. It may be a transition zone between the Mazatzal and Yavapai provinces.

No subdivisions have been made in the Mazatzal province in New Mexico. The potential suture boundaries between tectonostratigraphic blocks include, from north to south, the northern boundary of the Yavapai-Mazatzal transition zone, the Jemez lineament, the Morenci lineament, and the Grenville front at the southern edge of the Mazatzal province (Karlstrom et al., 2004). The Pinal and the Cochise blocks in Arizona were distinguished by the detrital zircon ages in sedimentary rocks (older than 1678 Ma in the Pinal block) and by the dominance of basinal metaturbidites in the Pinal block and volcanic rocks in the Cochise block (Eisele and Isachsen, 2001). The presence of detrital zircons older than 1.7 Ga and $\varepsilon_{Nd}(t)$ of +1.5 in metasedimentary rocks from the Burro Mountains makes them more similar to the metasedimentary rocks in the Pinal block, but the Pinal block in Arizona has no basement exposed and was interpreted as a continental margin accretionary prism. The Burro and San Andres Mountains have both basement (in the granitic gneisses) and metasedimentary rocks, so cannot be a direct correlative to the Pinal block based on lithology. The New Mexico rocks are clearly distinct from those in the Cochise block because they are generally older, have more granites, and have older detrital zircon ages. For this reason, we put a boundary between the Cochise block and the study area in southwestern New Mexico (Fig. 2). In general, the ages of intrusive, extrusive, and metasedimentary rocks in southern New Mexico are broadly similar to the range of values for rocks in northern New Mexico (Karlstrom et al., 2004), so we do not feel confident that a separate block can be delineated between these two areas.

It is possible that some of the boundaries assigned in Arizona are not major sutures but instead represent steeply dipping shear zones exposing disparate crustal levels (Bowring and Karlstrom, 1990). In New Mexico, exposure of similar crustal levels has resulted in similar rocks being exposed across the region, and therefore block boundaries are not easily recognized. Only regions with exposed mafic rocks can be more clearly recognized as sutures, such as at the Pinal-Cochise block boundary (Eisele and Isachsen, 2001) and in the Mazatzal block and perhaps extending into the Jemez lineament (Dann, 1997; Strickland et al., 2003).

Onset and Duration of the Mazatzal Orogeny

Estimates of the ages of onset and duration of the Mazatzal orogeny have been hindered by the high temperatures of younger regional amphibolite facies metamorphism that regionally reset $^{40}Ar/^{39}Ar$ ages ca. 1.4 Ga (Karlstrom et al., 1997; Shaw et al., 2005; Amato et al., 2006). Most constraints of the timing of deformation have come from U-Pb dating of deformed and undeformed igneous rocks (Fig. 13). It is possible that some of these rocks have fabrics that may have formed from processes other than deformation, such as magmatic flow. Many of the studies cited here do not provide sufficient detail about the rock textures to evaluate this problem, and therefore rocks reported as deformed are assumed to be deformed. Some undeformed rocks could have escaped deformation owing to their rheology and the local pressure-temperature conditions.

The main phase of deformation in the Burro Mountains must have ended before 1633 Ma, the age of the gabbro, based on the presence of undeformed porphyroblasts within the contact aureole of the gabbro. All of the metasedimentary rocks and all of the pre-1.63 Ga igneous rocks in the Burro Mountains share a deformational fabric (Fig. 6), and most of the abundant ca. 1.4 Ga plutons in the region are undeformed (Amato et al., 2006). In Arizona, the timing of the Mazatzal orogeny originally was bracketed to between 1675 and 1625 Ma (Silver and Deutsch, 1963; Silver, 1965, 1978; Conway and Silver, 1989), based on U-Pb dating of deformed volcanic rocks and the undeformed 1625 ± 10 Ma Johnny Lyon granodiorite. This granodiorite was recently redated as 1643 ± 4 Ma (Eisele and Isachsen, 2001).

An evaluation of all of the available data for deformed and undeformed rocks emplaced in the Mazatzal province before 1600 Ma (Table DR5; see footnote 1) suggests that most rocks emplaced before 1650 Ma are deformed, and the majority of those emplaced after this time are either undeformed or locally deformed. A weighted mean of the youngest nine deformed rocks (Table DR5) is 1654 ± 3 Ma (MSWD = 1.2), and we believe that

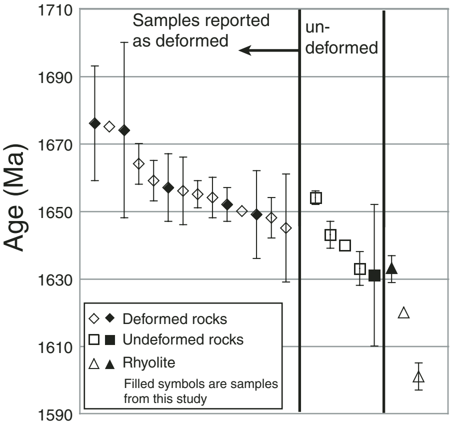

Figure 13. Summary of ages from three groups of Mazatzal province rocks: deformed and undeformed granitoids, and rhyolites, some of which have been reported as deformed. Data sources are in Table DR5 (see footnote 1).

widespread, regional deformation must have occurred after this time but before emplacement of the 1643 Ma Johnny Lyon granodiorite and the 1633 Ma gabbro in the Burro Mountains. Our detrital zircon data suggest that the Yavapai province was near the Mazatzal province ca. 1650 Ma, and we suggest that this sedimentation occurred just before or during the Mazatzal orogeny, which represents the main collision between these two provinces.

An exception to these constraints is the interpretation that a 1.62 Ga rhyolite in the McDowell Mountains of Arizona (Karlstrom and Bowring, 1993) and a 1.60 Ga rhyolite in the Manzano Mountains of northern New Mexico (Luther et al., 2006) are both deformed. The data for these samples have not yet been published, but it is possible that these were deformed during a younger event that postdates the Mazatzal orogeny. Several published references to the Mazatzal orogeny duration from 1.65 to 1.60 Ga may be overestimating its duration as a regionally significant deformational event if, as the data suggest, it may have ended before 1643 Ma in Arizona and before 1633 Ma in New Mexico.

Magmatism After the Mazatzal Orogeny and Before ca. 1.4 Ga

In southern New Mexico, magmatism following the main period of Mazatzal deformation is represented by: (1) the 1633 Ma gabbro in the Burro Mountains; (2) the weakly foliated granite from the San Andres Mountains dated as 1632 ± 24 Ma (Roths, 1991) and 1631 ± 21 Ma (this study); (3) metamorphic overgrowths on a gneiss from the San Andres Mountains dated at 1617 ± 11 Ma; and (4) the metarhyolite from the Burro Mountains at 1633 ± 8 Ma.

We concur with Bickford and Hill (2007) that there is good evidence for extension in southern Laurentia, but we suggest that it mainly occurred after the Yavapai-Mazatzal accretion during the Mazatzal orogeny at 1.65–1.64 Ga. The 1633 gabbro in the Burro Mountains has ε_{Nd} values of +4.2 and depleted mantle model ages of ca. 1650 Ma and is therefore a juvenile rock (Rämö et al., 2003). This rock was described as a tholeiite with ocean island basalt chemistry and was interpreted to have intruded during local crustal extension (Rämö et al., 2003). Our new finding of coeval granitic magmatism in the San Andres Mountains, as well as abundant amphibolites that are coeval based on shared deformational fabrics with the granites, indicates that both felsic and mafic, and therefore bimodal, magmatism occurred at this time. This is consistent with igneous activity during extension ca. 1630 Ma.

Tectonic Model for Mazatzal Evolution

A model that incorporates the geochemistry, ages of the rocks, and the timing of their deformation must include the following. (1) Subduction-related magmatism within an oceanic arc setting created the bulk of the Mazatzal province crust from ca. 1680 Ma to 1650 Ma. (2) Magmatism in northern New Mexico and southeastern Arizona may have been similar to that typical in island arcs dominated by mafic to intermediate rocks. (3) In southern New Mexico, the rocks have higher SiO_2 concentrations as well as high $\varepsilon_{Nd}(t)$, indicating that juvenile yet differentiated magmatism was occurring.

The entire Mazatzal province probably did not form as the result of magmatism above a single subduction zone. The southwest Pacific oceanic arcs are an analog for multiple smaller arcs in one region that could eventually be amalgamated and accreted to a continental margin during subduction. The variation in ages between interpreted arc rocks in northern New Mexico and those in southwestern Arizona indicates that it is likely that multiple arcs were active at different times. Recent work in the Mazatzal province in Arizona showed persuasive evidence for both arc (Eisele and Isachsen, 2001) and ophiolite rocks (Swift and Force, 2001) at the boundary between subblocks of the Mazatzal province. However, subduction complexes associated with many arcs, such as the Jurassic Talkeetna arc, are known to be in a state of erosion during their formation, and this would preclude their preservation in the geologic record (Clift et al., 2005).

As a series of arcs were translated closer to the southern Laurentia margin during subduction, thrusting is likely to have taken place during accretion. Sedimentation in these arcs may have occurred near 1650 Ma based on the age of the youngest zircon populations in the Burro Mountains. At around the same time as this deposition, 1650 Ma, a major regional deformational event occurred as these arcs accreted to the margin during the Mazatzal orogeny. After 1650 Ma, subduction could have continued in Arizona with extension occurring in southern New Mexico as the crust responded to the earlier thickening from accretion, or perhaps extended during backarc extension. By 1630 Ma, major magmatism in the Mazatzal province ceased, with the exception of localized rhyolite magmatism from 1630 Ma to ca. 1600 Ma. A period of magmatic and tectonic quiescence lasted until ca. 1460 Ma.

All of the tectonic processes inferred to have affected this region are known from examples in Phanerozoic rocks. Subduction, accretion, and postcollisional extension are common in orogenic belts worldwide. This study provides a well-characterized example of pre-Phanerozoic tectonic events, inferred from structural analysis, geochemistry, and geochronology, that may help understand other orogenic belts where important contextual information is absent.

CONCLUSIONS

The main conclusions from this study of Paleoproterozoic rocks in southern New Mexico are: (1) Nd isotope ratios in metasedimentary rocks yield $\varepsilon_{Nd}(t)$ of +1.4 to +2.5. Granites and granitic gneisses have $\varepsilon_{Nd}(t)$ of –1.2 to +4.3. Amphibolite has $\varepsilon_{Nd}(t)$ of +4.2. These $\varepsilon_{Nd}(t)$ values suggest juvenile mantle-derived magmatism, or that these rocks derived from the melting of crustal rocks that had only recently crystallized. (2) Pre-orogenic magmatism occurred from 1675 to 1650 Ma. (3) Sedimentation occurred until at least 1646 Ma and detritus was derived from both Mazatzal and Yavapai province sources. (4) Deformation associated with the Mazatzal orogeny ceased sometime between 1650 and 1633 Ma in New Mexico, and was likely over by 1643 Ma in southeastern Arizona. (4) Post-Mazatzal orogeny magmatism occurred from 1633 to 1620 Ma. (5) Extension at 1630 Ma is indicated by bimodal magmatism in the Burro and San Andres Mountains. (6) A hiatus in magmatism occurred from ca. 1625 Ma to 1460 Ma. (7) Deformation associated with rhyolites with ages of 1633 Ma (this study), 1620 Ma, and 1601 Ma (northern New Mexico and Arizona) may be related to deformation younger than the Mazatzal orogeny, as regional deformation is interpreted to have ceased by 1643 Ma. Models for an extensional tectonic setting prior to 1650 Ma were not supported by these new data from southern New Mexico because of the lack of evidence for inherited material, the presence of juvenile mantle-derived magmatism, and a possible subduction signature in the intrusive rocks.

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REFERENCES CITED

Alford, D.E., 1987, Geology and geochemistry of the Hembrillo Canyon Succession, San Andres, Sierra, and Dona Ana Counties, New Mexico [M.S. thesis]: Socorro, New Mexico Institute of Mining and Technology, 180 p.

Amato, J.M., Boullion, A.O., Sanders, A.E., Gehrels, G., Andronicos, C.L., Heizler, M.T., and Farmer, G.L., 2006, Magmatism, metamorphism, and deformation of Proterozoic Mazatzal Province crust: A comprehensive case study from the Burro Mountains, southwest New Mexico: Geological Society of America Abstracts with Programs, v. 38 no. 6, p. 4.

Anders, E., and Grevesse, N., 1989, Abundances of the elements: Meteoritic and solar: Geochimica et Cosmochimica Acta, v. 53, p. 197–214, doi: 10.1016/0016-7037(89)90286-X.

Bachman, G.O., and Harbour, R.L., 1970, Geologic map of the northern part of the San Andres Mountains, central New Mexico: U.S. Geological Survey, scale 1:62,500.

Bachman, G.O., and Myers, D.A., 1969, Geology of the Bear Peak Area, Dona Ana County New Mexico: U.S. Geological Survey Bulletin 1271-C, p. 1–46.

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, doi: 10.1130/0016-7606(1987)99<674:PCHOTW>2.0.CO;2.

Bickford, M.E., and Hill, B.M., 2007, Does the arc accretion model adequately explain the Paleoproterozoic evolution of southern Laurentia?: An expanded interpretation: Geology, v. 35, p. 167–170, doi: 10.1130/G23174A.1.

Boullion, A.O., 2006, The tectonic history of Proterozoic crust in the Mazatzal Province: Geochronology, geochemistry, and kinematic analysis of the intrusive rocks of the Burro Mountains, southwest New Mexico [M.S. thesis]: Las Cruces, New Mexico, New Mexico State University, 108 p.

Bowring, S.A., and Karlstrom, K.E., 1990, Growth, stabilization, and reactivation of Proterozoic lithosphere in the southwestern United States: Geology, v. 18, p. 1203–1206, doi: 10.1130/0091-7613(1990)018<1203:GSAROP>2.3.CO;2.

Clemons, R.E., 1998, Geology of the Florida Mountains, southwestern New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 43, 112 p.

Clift, P.D., Pavlis, T., DeBari, S.M., Draut, A.E., Rioux, M., and Kelemen, P.K., 2005, Subduction erosion of the Jurassic Talkeetna-Bonanza arc and the Mesozoic accretionary tectonics of western North America: Geology, v. 33, p. 881–884, doi: 10.1130/G21822.1.

Condie, K.C., 1980, The Tijeras Greenstone: Evidence for depleted upper mantle beneath New Mexico during the Proterozoic: Journal of Geology, v. 88, p. 603–609.

Condie, K.C., 1981, Precambrian rocks of the southwestern United States and adjacent areas of Mexico: New Mexico Bureau of Mines and Mineral Resources Resource Map 13**,** scale 1:1,500,000.

Condie, K.C., 1982, Plate tectonics model for Proterozoic continental accretion in the southwestern United States: Geology, v. 10, p. 37–42, doi: 10.1130/0091-7613(1982)10<37:PMFPCA>2.0.CO;2.

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 35, 58 p.

Conway, C.M., and Silver, L.T., 1989, Early Proterozoic rocks (1710–1615 Ma) in central to southeastern Arizona: Arizona Geological Society Digest, v. 17, p. 165–186.

Dalziel, I.W.D., 1991, Pacific margins of Laurentia and East Antarctica–Australia as a conjugate rift pair: Evidence and implications for an Eocambrian supercontinent: Geology, v. 19, p. 598–601, doi: 10.1130/0091-7613(1991)019<0598:PMOLAE>2.3.CO;2.

Dann, J.C., 1997, Pseudostratigraphy and origin of the Early Proterozoic Payson ophiolite, central Arizona: Geological Society of America Bulletin, v. 109, p. 347–365, doi: 10.1130/0016-7606(1997)109<0347:PAOOTE>2.3.CO;2.

DePaolo, D.J., 1981, Neodymium isotopes in the Colorado Front Range and crust-mantle evolution in the Proterozoic: Nature, v. 291, p. 193–196, doi: 10.1038/291193a0.

Duebendorfer, E.M., Chamberlain, K.R., and Jones, C.S., 2001, Paleoproterozoic tectonic history of the Cerbat Mountains, northwestern Arizona: Implications for crustal assembly in the southwestern United States: Geological Society of America Bulletin, v. 113, p. 575–590, doi: 10.1130/0016-7606(2001)113<0575:PTHOTC>2.0.CO;2.

Duebendorfer, E.M., Chamberlain, K.R., and Fry, B., 2006, Mojave-Yavapai boundary zone, southwestern United States: A rifting model for the formation of an isotopically mixed crustal boundary zone: Geology, v. 34, p. 681–684, doi: 10.1130/G22581.1.

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, doi: 10.2475/ajs.301.9.773.

Evans, K.V., and Clemons, R.E., 1988, Cambrian-Ordovician (500 Ma) alkalic plutonism in southwestern New Mexico: U-Th-Pb isotopic data from the Florida Mountains: American Journal of Science, v. 288, p. 735–755.

Farmer, G.L., Broxton, D.E., Warren, R.G., and Pickthorn, W., 1991, Nd, Sr, and O isotopic variations in metaluminous ash-flow tuffs and related volcanic rocks at the Timber Mountain/Oasis Valley Caldera Complex, SW Nevada: Implications for the origin and evolution of large-volume silicic magma bodies: Contributions to Mineralogy and Petrology, v. 109, p. 53–68, doi: 10.1007/BF00687200.

Farmer, G.L., Bowring, S.A., Matzel, J., Espinosa Maldonado, G., Fedo, C., and Wooden, J., 2005, Paleoproterozoic Mojave province in northwestern Mexico?: Isotopic and U-Pb zircon geochronologic studies of Precambrian and Cambrian crystalline and sedimentary rocks, Caborca, Sonora, *in* Anderson, T.H., et al., eds., The Mojave-Sonora megashear hypothesis: Development, assessment, and alternatives: Geological Society of America Special Paper 393, p. 183–198.

Finnell, T.L., 1987, Geologic map of the Cliff quadrangle, Grant County, New Mexico: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-1768**,** scale 1:50,000.

Grambling, J.A., Williams, M.L., and Mawer, C.K., 1988, Proterozoic tectonic assembly of New Mexico: Geology, v. 16, p. 724–727, doi: 10.1130/0091-7613(1988)016<0724:PTAONM>2.3.CO;2.

Hawkins, D.P., Bowring, S.A., Ilg, B.R., Karlstrom, K.E., and Williams, M.L., 1996, U-Pb geochronologic constraints on Proterozoic crustal evolution: Geological Society of America Bulletin, v. 108, p. 1167–1181, doi: 10.1130/0016-7606(1996)108<1167:UPGCOT>2.3.CO;2.

Hedlund, D.C., 1978a, Geologic map of the Burro Peak quadrangle, Grant County, New Mexico: Reston, Virginia, U.S. Geological Survey Miscellaneous Field Studies, Map MF-1040, scale 1:24,000.

Hedlund, D.C., 1978b, Geologic map of the C Bar Ranch Quadrangle, Grant County, New Mexico: Reston, Virginia, U.S. Geological Survey Miscellaneous Field Studies, Map MF-1039, scale 1:24,000.

Hedlund, D.C., 1978c, Geologic map of the Farewell Hill Quadrangle, Grant County, New Mexico: Reston, Virginia, U.S. Geological Survey Miscellaneous Field Studies, Map MF-1033, scale 1:24,000.

Hedlund, D.C., 1978d, Geologic map of the Gold Hill Quadrangle, Grant County, New Mexico: Reston, Virginia, U.S. Geological Survey Miscellaneous Field Studies, Map MF-1035, scale 1:24,000.

Hedlund, D.C., 1978e, Geologic map of the Ninetysix Ranch Quadrangle, Grant County, New Mexico: Reston, Virginia, U.S. Geological Survey Miscellaneous Field Studies, Map MF-1034, scale 1:24,000.

Hedlund, D.C., 1978f, Geologic map of the Tyrone Quadrangle, Grant County, New Mexico: Reston, Virginia, U.S. Geological Survey Miscellaneous Field Studies, Map MF-1037, scale 1:24,000.

Hedlund, D.C., 1978g, Geologic map of the White Signal Quadrangle, Grant County, New Mexico: Reston, Virginia, U.S. Geological Survey Miscellaneous Field Studies, Map MF-1041, scale 1:24,000.

Hedlund, D.C., 1978h, Geologic map of the Wind Mountain Quadrangle, Grant County, New Mexico: Reston, Virginia, U.S. Geological Survey Miscellaneous Field Studies, Map MF-1031, scale 1:24,000.

Hedlund, D.C., 1980a, Geologic map of the Redrock NE quadrangle, Grant County, New Mexico: U.S. Geological Survey Miscellaneous Field Studies Map MF-1264, scale 1:24,000.

Hedlund, D.C., 1980b, Geologic map of the Redrock NW quadrangle, Grant County, New Mexico: Reston, Virginia, U.S. Geological Survey Miscellaneous Field Studies, Map MF-1263, scale 1:24,000.

Hedlund, D.C., 1980c, Geologic map of the Redrock SE quadrangle, Grant County, New Mexico: Reston, Virginia, U.S. Geological Survey Miscellaneous Field Studies, Map MF-1265, scale 1:24,000.

Hewitt, C.H., 1959, Geology and mineral deposits of the northern Big Burro Mountains–Redrock area, Grant County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin, v. 60, 151 p.

Hill, B.M., and Bickford, M.E., 2001, Paleoproterozoic rocks of central Colorado: Accreted arcs or extended older crust?: Geology, v. 29, p. 1015–1018, doi: 10.1130/0091-7613(2001)029<1015:PROCCA>2.0.CO;2.

Johnsen, M., DeBari, S., and Rioux, M., 2007, The felsic plutonic core of the western Talkeenta island arc crustal section, Alaska: Its formation and implications for crustal growth along continental margins: Geological Society of America Abstracts with Programs, v. 39, no. 4, p. 72–73.

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.

Karlstrom, K.E., and Bowring, S.A., 1993, Proterozoic orogenic history of Arizona, *in* Reed, J.C., et al., eds., Precambrian: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. C-2, p. 188–211.

Karlstrom, K.E., Bowring, S.A., and Conway, C.M., 1987, Tectonic significance of an Early Proterozoic two-province boundary in central Arizona: Geological Society of America Bulletin, v. 99, p. 529–538, doi: 10.1130/0016-7606(1987)99<529:TSOAEP>2.0.CO;2.

Karlstrom, K.E., Doe, M.F., Wessels, R.L., Bowring, S.A., Dann, J.C., and Williams, M.L., 1990, Juxtaposition of Proterozoic crustal blocks: 1.65–1.60 Mazatzal orogeny, *in* Gehrels, G.E., and Spencer, J.E., eds., Geologic excursions through the Sonoran desert region, Arizona and Sonora*:* Arizona Geological Survey Special Paper 7, p. 114–123.

Karlstrom, K.E., Dallmeyer, R.D., and Grambling, J.A., 1997, ^{40}Ar/^{39}Ar evidence for 1.4 Ga regional metamorphism in New Mexico: Implications for thermal evolution of lithosphere in the southwestern USA: Journal of Geology, v. 105, p. 205–223.

Karlstrom, K.E., Chamberlain, R.M., Connell, S.D., Brown, C., Nyman, M., Cavin, W.J., Parchman, M.A., Cook, C., and Sterling, J., 1998, Geology of the Mount Washington 7.5-minute quadrangle, Bernalillo and Valencia Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open-File Report OF-DM-27, scale 1:24,000.

Karlstrom, K.E., Harlan, S.S., Williams, M.L., McLelland, J., Geissman, J.W., and Ahall, K., 1999, Refining Rodinia: Geological evidence for the Australia–western U.S. connection in the Proterozoic: GSA Today, v. 9, no. 10, p. 1–7.

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: Canada, New Mexico Geological Society, p. 1–34.

Kelemen, P.B., Shimizu, N., and Dunn, T., 1993, Relative depletion of niobium in some arc magmas and the continental crust: Partitioning of K, Nb, La, and Ce during melt/rock reaction in the upper mantle: Earth and Planetary Science Letters, v. 120, p. 111–134, doi: 10.1016/0012-821X(93)90234-Z.

Kelemen, P.B., Hanghoj, K., and Greene, A.R., 2003, One view of the geochemistry of subduction-related magmatic arcs, with an emphasis on primitive andesite and lower crust, *in* Rudnick, R.L., ed., Treatise on geochemistry—The crust: New York, Elsevier Science, p. 593–659.

Kottlowski, F.E., Flower, R.H., Thompson, M.L., and Foster, R.W., 1956, Stratigraphic studies of the San Andres Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 1, 132 p.

Ludwig, K.R., 2003, Isoplot/Ex 3.00: A geochronological toolkit for Microsoft Excel: Berkeley Geochronology Center Special Publication 4.

Luther, A.L., Jones, J.V., III, Shastri, L.L., Williams, M.L., Jercinovic, M., and Karlstrom, K.E., 2006, A new age of 1600 Ma for deposition of the Upper Manzano Group: Evidence for a progressive (1.66–1.60 Ga) Mazatzal orogeny, central New Mexico: New Mexico Geology, v. 28, p. 60.

Mack, G.H., 2004, Middle and late Cenozoic crustal extension, sedimentation, and volcanism in the southern Rio Grande rift, Basin and Range, and southern transition zone of southwestern New Mexico, *in* Mack, G.H., and Giles, K.A., eds., The geology of New Mexico: A geologic history: Canada, New Mexico Geological Society, p. 389–406.

MacLean, W.H., 1990, Mass change calculations in altered rock series: Mineralium Deposita, v. 25, p. 44–49.

Magnani, M.B., Miller, K.C., Levander, A., and Karlstrom, K., 2004, The Yavapai-Mazatzal boundary: A long lived assembly structure in the lithosphere of southwestern North America: Geological Society of America Bulletin, v. 116, p. 1137–1142, doi: 10.1130/B25414.1.

Moores, E.M., 1991, Southwest U.S.–East Antarctic (SWEAT) connection: A hypothesis: Geology, v. 19, p. 425–428, doi: 10.1130/0091-7613(1991)019<0425:SUSEAS>2.3.CO;2.

Nelson, B.K., and DePaolo, D.J., 1985, Rapid production of continental crust 1.7 to 1.9 b.y. ago: Nd isotopic evidence from the basement of the North American midcontinent: Geological Society of America Bulletin, v. 96, p. 746–754, doi: 10.1130/0016-7606(1985)96<746:RPOCCT>2.0.CO;2.

Pearce, J.A., and Cann, J.R., 1973, Tectonic setting of basic volcanic rocks determined using trace element analyses: Earth and Planetary Science Letters, v. 19, p. 290–300, doi: 10.1016/0012-821X(73)90129-5.

Rämö, O.T., and Calzia, J.P., 1998, Nd isotopic composition of cratonic rocks in the southern Death Valley region: Evidence for a substantial Archean source component in Mojavia: Geology, v. 26, p. 891–894, doi: 10.1130/0091-7613(1998)026<0891:NICOCR>2.3.CO;2.

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, doi: 10.1130/0091-7613(2003)031<0335:IMMICM>2.0.CO;2.

Reed, J.C., Jr., Ball, T.T., Farmer, G.L., and Hamilton, W.B., 1993, A broader view: Origin and significance of Nd isotopic provinces within the Precambrian crust of the conterminous United States, *in* Reed, J.C., Jr., Bickford, M.E., Houston, R.S., Link, P.K., Rankin, D.W., Sims, P.K., and Van Schmus, W.R., eds., Precambrian: Conterminous U.S.: Boulder, Geological Society of America, p. 597-636.

Reiche, P., 1949, Geology of the Manzanita and north Manzano Mountains, New Mexico: Geological Society of America Bulletin, v. 60, p. 1183–1212, doi: 10.1130/0016-7606(1949)60[1183:GOTMAN]2.0.CO;2.

Roths, P., 1991, Geology of Proterozoic outcrops in Dead Man and Little San Nicolas Canyons, southern San Andres Mountains, New Mexico: New Mexico Geological Society 42nd Field Conference Guidebook, p. 91–96.

Ruks, T.W., Piercey, S.J., Ryan, J.J., Villeneuve, M.E., and Creaser, R.A., 2006, Mid- to late Paleozoic K-feldspar augen granitoids of the Yukon-Tanana terrane, Yukon, Canada: Implications for crustal growth and tectonic evolution of the northern Cordillera: Geological Society of America Bulletin, v. 118, p. 1212–1231, doi: 10.1130/B25854.1.

Sanders, A.O., 2003, Age of deposition and metamorphism of deformed Proterozoic metasedimentary rocks in the Burro Mountains, southwest New Mexico [M.S. thesis]: Las Cruces, New Mexico, New Mexico State University, 198 p.

Seager, W.R., 1981, Geology of Organ Mountains and southern San Andres Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 36, 97 p.

Seager, W.R., 2004, Laramide (Late Cretaceous–Eocene) tectonics of southwestern New Mexico, *in* Mack, G.H., and Giles, K.A., ed., The geology of New Mexico: A geologic history: Canada, New Mexico Geological Society, p. 183–202.

Serna, A.M., 2006, Geochronology and deformation of the Proterozoic rocks of southern San Andres Mountains, south-central New Mexico [M.S. thesis]: Las Cruces, New Mexico, New Mexico State University, 89 p.

Shaw, C.A., and Karlstrom, K.E., 1999, The Yavapai-Mazatzal crustal boundary in the Southern Rocky Mountains: Rocky Mountain Geology, v. 34, p. 37–52, doi: 10.2113/34.1.37.

Shaw, C.A., Heizler, M.T., and Karlstrom, K.E., 2005, ^{40}Ar/^{39}Ar thermochronologic record of 1.45–1.35 Ga intracontinental tectonism in the southern Rocky Mountains: Interplay of conductive and advective heating with intracontinental deformation, *in* Karlstrom, K.E., and Keller, G.R., eds., The Rocky Mountain region—An evolving lithosphere: Tectonics, geochemistry, and geophysics: American Geophysical Union Geophysical Monograph 154, p. 163–184.

Silver, L.T., 1965, Mazatzal orogeny and tectonic episodicity, *in* Abstracts for 1964: New York, Geological Society of America Special Paper 82, p. 185–186.

Silver, L.T., 1978, Precambrian formations and Precambrian history in Cochise County, southeastern Arizona, *in* Callender, J.F., et al., eds., Land of Cochise: New Mexico Geological Society 29th Annual Field Conference Guidebook, p. 157–163.

Silver, L.T., and Deutsch, S., 1963, Uranium-lead isotopic variations in zircons: A case study: Journal of Geology, v. 71, p. 721–758.

Stacey, J.S., and Hedlund, D.C., 1983, Lead-isotopic compositions of diverse igneous rocks and ore deposits from southwestern New Mexico and their implications for Early Proterozoic crustal evolution in western United States: Geological Society of America Bulletin, v. 94, p. 43–57, doi: 10.1130/0016-7606(1983)94<43:LCODIR>2.0.CO;2.

Strickland, D., Heizler, M.T., Selverstone, J., and Karlstrom, K.E., 2003, Proterozoic evolution of the Zuni Mountains, western New Mexico: Relationship to the Jemez lineament and implications, *in* Lucas, S.G., et al., eds., Geology of the Zuni Plateau: New Mexico Geological Society 54th Annual Field Conference Guidebook, p. 109–118.

Swift, P.N., and Force, E.R., 2001, Subduction-margin assemblages in the Proterozoic Pinal and Cochise blocks, southeastern Arizona: American Journal of Science, v. 301, p. 755–772, doi: 10.2475/ajs.301.9.755.

Thompson, R.N., 1982, Magmatism of the British Tertiary Volcanic Province: Scottish Journal of Geology, v. 18, p. 50–107.

Vollbrecht, K.M., 1997, Constraints on the timing and character of Proterozoic deformation and metamorphism in the San Andres Mountains of south-central New Mexico [M.S. thesis]: Socorro, New Mexico Institute of Mining and Technology, 74 p.

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, doi: 10.2113/34.1.53.

Wilson, E.D., 1939, Pre-Cambrian Mazatzal revolution in central Arizona: Geological Society of America Bulletin, v. 50, p. 1113–1163.

Wood, D.A., 1980, The application of a Th-Hf-Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary volcanic province: Earth and Planetary Science Letters, v. 50, p. 11–30, doi: 10.1016/0012-821X(80)90116-8.

Wooden, J.L., and Miller, D.M., 1990, Chronologic and isotopic framework for Early Proterozoic crustal evolution in the eastern Mojave desert region, California: Journal of Geophysical Research, v. 95, p. 20,133–20,146.

Woodward, L.A., 1970, Precambrian rocks of southwestern New Mexico, *in* Woodward, L.A., ed., Guidebook of the Tyrone–Big Hatchet Mountains–Florida Mountains region: New Mexico Geological Society 21st Annual Field Conference Guidebook, p. 27–31.

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