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INTERMITTENT PROTEROZOIC PLUTONIC MAGMATISM AND NEOPROTEROZOIC COOLING HISTORY IN THE CABALLO MOUNTAINS, SIERRA COUNTY, NEW MEXICO; PRELIMINARY RESULTS

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ABSTRACT—New mapping, geochemistry, and biotite $^{40}Ar/^{39}Ar$ thermochronology of granitic and metamorphic rocks in the Caballo Mountains indicate a period of ~1480 Ma plutonism followed by cooling to ~300°C by 1411±3 Ma. Isotope and geochemistry data allow correlation with other Proterozoic terrains in southern New Mexico. At least five Proterozoic granitic plutons are found in the Caballo Mountains; the Caballo granite, Longbottom Canyon granite/granodiorite pluton, Northern Caballo granite, Palomas Gap granite, and granite dikes that intruded ~1680 Ma supracrustal amphibolite and felsic gneiss and granite gneiss. The Longbottom Canyon pluton and Caballo granite yield indistinguishable U/Pb zircon derived intrusion ages of 1486±16 and 1487±24 Ma (Amato and Becker, 2012, this guidebook). Nd isotope data support ~1480 Ma magmatism in the region and suggest that the Palomas Gap granite also may be a ~1480 Ma intrusion. No direct dating is available for the granite dikes, however a complex $^{40}Ar/^{39}Ar$ biotite age spectrum is permissive of one dike being part of the ~1480 Ma intrusive suite. Small, alkaline igneous dikes and near-vertical pipes intruded the Proterozoic granitic rocks in several areas of the Caballo Mountains and are unconfomrably overlain by the Cambrian-Ordovician Bliss Formation (north and south of Palomas Gap, Longbottom Canyon, Apache Gap area, and the Red Hills area of the southern Caballo Mountains). Alkaline magmatism occurs in the Caballo Mountains and may be associated with regional Cambrian-Ordovician magmatic episodes, but no direct radiometric dating has yet identified intrusions of this age in the Caballo Mountains. These alkaline intrusives, which have been interpreted to be Cambrian-Ordovician in age based upon field relationships and regional correlations may indeed be older as suggested. Additional $^{40}Ar/^{39}Ar$ thermochronology on K-feldspar was conducted. K-feldspar age spectra are variable with 3 samples yielding age gradients between about 1100 to 800 Ma that support cooling from ~275°C to 175°C related to Grenville contraction and associated exhumation. Ages as young as ~70 Ma in the K-feldspar age spectra are consistent with Phanerozoic burial followed by late Tertiary rift-related exhumation. A variety of mineral deposits are found in the igneous rocks in the Caballo Mountains, and most are small, low grade, and uneconomic. Only the gold veins in Proterozoic rocks, placer gold deposits, and REE-U-Th veins in possible Cambrian-Ordovician alkaline igneous rocks and associated metasomatic episyenites have future mineral resource potential.

INTRODUCTION

In southern New Mexico, Texas, and Arizona (Fig. 1), four major Proterozoic igneous pulses occurred at 1650-1630 Ma , 1480-1340 Ma (granite-rhyolite province), ~1220 Ma, and 1120-1080 Ma. In New Mexico and southern Colorado, these Proterozoic magmatic pulses were followed by a Cambrian-Ordovician alkaline and carbonatite igneous event with ages between 457 and 664 Ma (McMillan and McLemore, 2004). Outcrops representing these events are scattered throughout New Mexico, Texas, and Arizona (Fig. 1, 2); the Proterozoic rocks in the Caballo Mountains are one area where some of these magmatic events are found together.

The Caballo Mountains are an east-dipping fault block along the eastern Rio Grande Rift in central New Mexico (Fig. 1) and are comprised of rocks ranging in age from Proterozoic to Recent. The basement plutonic rocks form the lower slopes of the Caballo Mountains and include at least six different granitic bodies; the Caballo granite, Longbottom granite/granodiorite pluton, Northern Caballo granite, granite dikes, Palomas Gap pluton, and alkaline igneous dikes and pipes that intruded an older ~1680 Ma supracrustal amphibolites, felsic gneiss and granite gneiss (Fig. 2; Condie and Budding, 1979; Bauer and Lozinsky, 1986; McLemore, 1986; Seager and Mack, 2003, 2005; Amato and Becker, 2012, this guidebook). The Caballo granite was defined by Condie and Budding (1979) and the Longbottom Canyon granodiorite by Bauer and Lozinsky (1986). Because the Long-

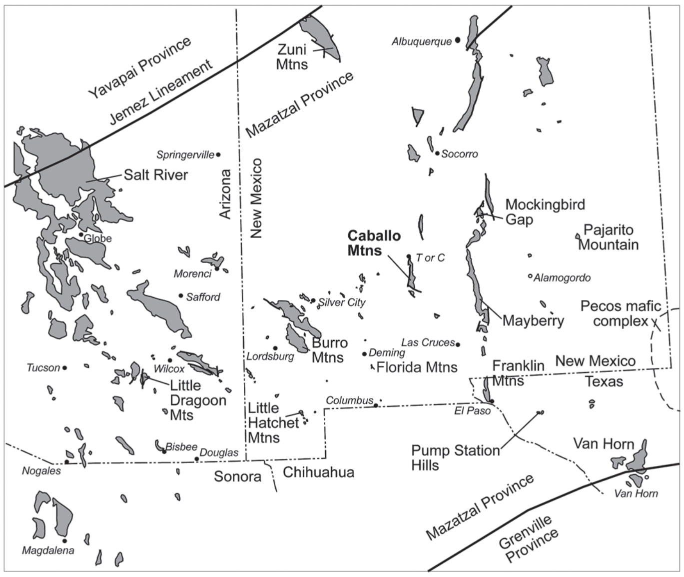

FIGURE 1. Areas of Proterozoic exposure in southwestern United States and Mexico, showing location of Caballo Mountains (modified from Condie, 1981).

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bottom Canyon granodiorite ranges in composition from granodiorite to granite, it is best called the Longbottom Canyon pluton (Amato and Becker, 2012, this guidebook).

The Northern Caballo granite is defined in this paper to include the granitic rocks north of Longbottom Canyon and south of the Palomas Gap pluton (Fig. 2; formerly the unnamed northern granite of Seager and Mack, 2003). The Palomas Gap pluton defined here includes the granitic rocks found in the Palomas Gap area (formerly syenite and granite of Condie and Budding, 1979 and the northern Red Hills granite of Seager and Mack, 2003).

Small, alkaline igneous dikes and near-vertical pipes intruded the Proterozoic granitic rocks in several areas of the Caballo Mountains and are unconformably overlain by the Cambrian-Ordovician Bliss Formation (Fig. 2): north and south of Palomas Gap, Longbottom Canyon, Apache Gap area, and the Red Hills area of the southern Caballo Mountains. Previously, these alkaline igneous rocks were reported only from the Red Hills area in the southern Caballo Mountains (Staatz et al., 1965; McLemore, 1986). These distinctive red alkaline igneous outcrops vary in lithology and include syenites, monzonites, quartz syenites, and monzogranites and are associated with metasomatic episyenite and REE-Th-U veins. The alkaline igneous rocks in the Red Hills (southern Caballo Mountains) were thought to be Cambrian-Ordovician by McLemore (1986) and McMillan and McLemore (2004) based upon field relationships and regional correlations. Geochronology to determine intrusion age is not yet available, however study has begun.

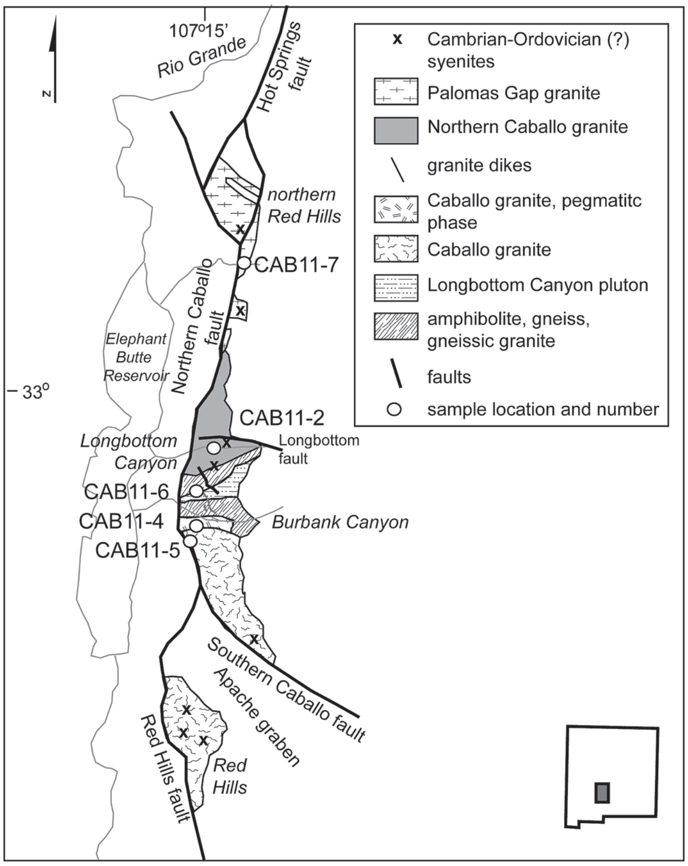


FIGURE 2. Simplified geologic map of the Proterozoic metamorphic and plutonic rocks and possible Cambrian-Ordovician alkaline rocks in the Caballo Mountains, Sierra County, New Mexico (modified from Condie and Budding, 1979; Seager and Mack, 2003; reconnaissance mapping by the senior author).

The Proterozoic and possible Cambrian-Ordovician metamorphic and plutonic rocks in the Caballo Mountains host a variety of mineral deposits, including REE-Th-U veins in alkaline igneous rocks (Staatz et al., 1965; McLemore, 1986; McLemore et al., 1988a, b), syenite/gabbro-hosted platinum group elements (PGE) in the metamorphic amphibolites, vein and replacement deposits in Proterozoic granitic rocks, Rio Grande Rift barite-fluorite-galena deposits, epithermal manganese deposits, and placer gold deposits.

The purposes of this report are to 1) summarize the geology of the basement metamorphic and igneous rocks in the Caballo Mountains, 2) present new $^{40}Ar/^{39}Ar$ and Nd isotopic data of some of these rocks, and 3) briefly describe the mineral resources hosted by the crystalline rocks. This report presents preliminary results and interpretations as mapping, geochemical, and geochronological studies are ongoing by the authors in the Caballo Mountains.

REGIONAL GEOLOGIC SETTING

Granitic magmatism throughout New Mexico, south Texas and southern Arizona can be divided into four phases. The Mazatzal orogeny, 1680-1600 Ma is the oldest recognized event in southern New Mexico and probably resulted from arc-continent collisions followed by rifting (Karlstrom and Bowring, 1988, 1993; Karlstrom et al., 1990; Karlstrom et al., 2004; Amato et al., 2008, 2011; Amato and Becker, 2012, this guidebook). A tectonic lull was followed by widespread mid-Proterozoic granitic plutonism and rhyolite volcanism at 1480-1340 Ma, the Laurentian Mesoproterozoic granite-rhyolite belt (Fig. 1; Stacey and Hedlund, 1983; Karlstrom and Bowring, 1988, 1993; Adams and Keller, 1996; Karlstrom et al., 1997; Karlstrom and Humphreys, 1998; Karlstrom et al., 2004; Amato et al., 2008, 2011; Amato and Becker, 2012, this guidebook). Traditionally, these anorogenic granites (A-type granites) of southwestern U.S. have been related to intracontinental rifting (Anderson, 1983), but this idea has been recently challenged by a model that relates them to mafic underplating in an overall transpressive tectonic regime (Frost and Frost, 1997; Karlstrom and Humphreys, 1998; Karlstrom et al., 2002, 2004).

The Grenville orogeny, extension, and formation of continental margin followed at 1300-1000 Ma (Adams and Keller, 1994, 1996; Karlstrom et al., 1997; Karlstrom and Humphreys, 1998; Barnes et al., 1999). The Grenville time in southwestern U.S. is characterized by 1) intrusion of the Pecos mafic intrusive complex and the Red Bluff Granite in southeastern New Mexico and west Texas, 2) the Redrock granite and associated anorthosites, and 3) other ~1220 Ma and 1120-1080 Ma mafic, volcanic, and A-type granitic intrusions in southern New Mexico, Texas, Arizona, and Mexico that reheated much of the older Proterozoic terrain (Keller et al., 1989; Adams and Keller, 1996; Smith et al., 1997; Mosher, 1998; Barnes et al., 1999; Reese et al., 2000; McLemore et al., 2000, 2002, 2012; Bickford et al., 2000; Rämö et al., 2003).

During the Cambrian-Ordovician, a period of alkaline and carbonatite magmatism and extension occurred in southern Colorado and New Mexico at ~500 Ma (McLemore and McKee, 1988; Evans and Clemons, 1988; McLemore et al., 1999; McMillan et al., 2000; McMillan and McLemore, 2004) followed by a Paleozoic period of basin formation and uplift as part of the Ancestral Rocky Mountains (Florida uplift, Pedregosa Basin; Ross and Ross, 1986). The Cambrian-Ordovician magmatic event is characterized by the intrusion of carbonatites, syenites, monzonites, and alkaline granites and associated with episyenites, K-metasomatism (i.e., fenitization) and REE-Th-U veins in alkaline rocks. This type of magmatic activity is consistent with continental rift and aborted rift systems, although geologic evidence such as rift-basin sediments and geophysical signatures are lacking to support a rift during this time period in New Mexico. Recognition of widespread Cambrian-Ordovician magmatic activity in New Mexico, evidence of relatively rapid uplift and erosion in the Florida Mountains (Evans and Clemons, 1988; Clemons, 1998; Ervin, 1998), and the presence of carbonatites (McLemore, 1983, 1987) suggest that New Mexico was not a simple passive margin during the Cambrian-Ordovician; but rather experienced sufficient extension to perturb the mantle and initiate magmatism (McMillan and McLemore, 2004). Thus, an aulacogen was proposed by McMillan and McLemore (2004) to exist in New Mexico during Cambrian and Early Ordovician time, similar to the Southern Oklahoma aulacogen of the same age (Larson et al. 1985; McConnell and Gilbert, 1990).

METHODOLGY

Investigations of the metamorphic and plutonic rocks in the Caballo Mountains by the senior author began in 1983 in order to assess their economic potential and tectonic setting (McLemore, 1986). Continued investigations occurred in 1995-1996, as part of the evaluation of mineral resources in Sierra and Otero Counties (Green and O'Neill, 1998). During 2010-2012, the authors continued investigations in the area in order to understand the age of the granitic rocks, the tectonic setting, and evaluate the mineral resource potential. Two graduate students are continuing these efforts.

Published and unpublished data were compiled and examined. Mineral occurrences, deposits, mines, prospects, and mills were identified, plotted on base maps, and compiled in the New Mexico Mines Database (McLemore et al., 2005a, b). Figure 2 is a simplified geologic map based upon Condie and Budding (1979), Bauer and Lozinsky (1986), McLemore (1986), Seager and Mack (2003, 2005), and preliminary field mapping at a scale of 1:12,000 by the senior author. Igneous rock lithologies were characterized on the basis of mineralogy and chemistry.

Selected samples of the Proterozoic and possible Cambrian-Ordovician rocks were collected and analyzed for major and trace element geochemistry (Appendices 1 and 2). Some of these analyses were previously reported by Bauer and Lozinsky (1986) and McLemore (1986).

Four samples of granitic rocks were collected in 2011 and analyzed by furnace incremental heating $^{40}Ar/^{39}Ar$ age spectrum

TABLE 1. Summary of ages of Proterozoic samples from the Caballo Mountains (UTM coordinates are NAD 27, Zone 13; locations in parenthesis are from Amato and Becker, 2012, this guidebook). Geologic units are defined by Condie and Budding (1979), Seager and Mack (2003), and this report.

Sample	Easting	Northing	Geologic Unit	Description	Integrated $^{40}Ar/^{39}Ar$ Age (K-feldspar) Ma	Integrated $^{40}Ar/^{39}Ar$ Age (biotite) Ma	U-Pb ages (Amato and Becker, 2012, this guidebook)
CAB11-7	291741	3659001	Palomas Gap granite	gray to pink granite, with quartz, feldspar	609.1 ± 1.0		
CAB11-4	289194	3647412	granite dike	white granite dike cutting Caballo granite containing quartz, feldspar, biotite	919 ± 1.3	1010.6 ± 1.6	
CAB11-2	289988	3651027	Northern Caballo granite	gray to tan, fine grained granite	1001.2 ± 1.5		
	(288863)	(3647322)	Caballo granite				1487 ± 24
CAB11-6	289182 (289799)	3649084 (3648809)	Longbottom granodiorite/ granite pluton	brown-gray porphyritic granodiorite to granite, large phenocrysts of microcline and plagioclase in a finer-grained matrix of quartz, plagioclase, microcline, biotite	1106.4 ± 1.5	1375.9 ± 1.7	1486 ± 16
	(288588)	(3649171)	gneissic granite				1681 ± 12

TABLE 2. Sm-Nd isotope data for the Palomas Gap granite and the Northern Caballo granite.

Sample	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd^{a}$	$^{143}Nd/^{144}Nd^{b}$	eNd[c]	TDM[d]
CAB11-7 Palomas Gap granite	9.10	46.74	0.1177	0.512054 ± 8	+3.3 (at 1450 Ma) -5.3 (at 609 Ma)	1565
CAB11-2 Northern Caballo granite	8.33	52.04	0.09676	0.511791 ± 7	+2.0 (at 1450 Ma) -3.8 (at 1001 Ma)	1627

Note: Whole-rock Sm-Nd isotope data by ID-TIMS at the Geological Survey of Finland (GTK) by second author.

[a] Error on $^{147}Sm/^{144}Nd$ is 0.5%

[b] $^{143}Nd/^{144}Nd$ normalized to $^{146}Nd/^{144}Nd = 0.7219$; reported error is $2\sigma_m$ in last significant digit

[c] Calculated using chondritic values of $^{143}Nd/^{144}Nd = 0.51264$ and $^{147}Sm/^{144}Nd = 0.1966$

[d] Depleted mantle model age (DePaolo, 1981)

method by the New Mexico Geochronological Research Laboratory at NMBGMR (Table 1; Appendix 3) in order to determine their thermal history. Laboratory methods are described at http://geoinfo.nmt.edu/labs/argon/home.html.

Two of the samples were analyzed for their Nd isotope composition (Table 2) at the Geological Survey of Finland by OTR. Sample powders (~150-250 mg) were totally-spiked with a ^{149}Sm-^{150}Nd tracer before dissolution. Samples were dissolved for a minimum of two days in a teflon bomb at 180°C in HF-HNO_3. After evaporation the samples were dissolved in HCl to obtain clear solutions. LREE were separated using standard cation exhange chromatography and Sm and Nd were purified using a modified version of the Teflon-HDEHP method of Richard et al. (1976). The total procedural blank was <300 pg for Nd. Isotopic ratios of Sm and Nd were measured on a VG SECTOR 54 mass spectrometer (those of Nd in dynamic mode). Repeated analyses of the La Jolla Nd standard gave $^{143}Nd/^{144}Nd$ of 0.511850 ± 0.000012 (mean and external 2σ error of 12 measurements). The external 2σ error on $^{143}Nd/^{144}Nd$ was thus 0.0025% and the Sm-Nd ratios are estimated to be accurate within 0.5%. The maximum error in the e_{Nd} values is ± 0.4 ε-units.

DESCRIPTION OF METAMORPHIC AND PLUTONIC ROCKS IN THE CABALLO MOUNTAINS

The Proterozoic rocks in the Caballo Mountains have been mapped by Doyle (1951), Kelley and Silver (1952), Staatz et al. (1965), Mason (1976), Condie and Budding (1979), Bauer and Lozinsky (1986), McLemore (1986), and Seager and Mack (1991, 1998, 2003, 2005). The Proterozoic metamorphic and plutonic rocks and possible Cambrian-Ordovician alkaline rocks are unconformably overlain by Paleozoic and Mesozoic sedimentary rocks and Tertiary volcanic and sedimentary rocks (Kelley and Silver, 1952; Mason, 1976; McLemore, 1986; Seager and Mack, 1991, 2003, 2005). Structural relationships are complex as rocks have been deformed by Proterozoic, Paleozoic, Laramide, and mid-Tertiary tectonic events.

Proterozoic metamorphic rocks

The oldest rocks in the Caballo Mountains are metamorphic rocks consisting of amphibolite, quartz-feldspathic schist (paragneiss), felsic gneiss, and granitic gneiss (orthogneiss) that are exposed in the Longbottom and Burbank Canyons. The foliation strikes east-west to northeast (Seager and Mack, 2003). The presence of amphibolite and sillmanite indicates amphibolite-grade metamorphism at a pre- or syn-kinematic temperature of ~500°C (Bauer and Lozinsky, 1986). The Longbottom Canyon, Caballo, Northern Caballo and Palomas Gap Granite plutons are all unconformably overlain by the Cambrian-Ordovician Bliss Sandstone.

Proterozoic granitic rocks

The Proterozoic granitic rocks include at least five granitic intrusions; including the Caballo granite, Longbottom Canyon pluton, Northern Caballo granite, Palomas Gap granite, and granite dikes. The Longbottom Canyon pluton intruded the metamorphic complex, is concordant with metamorphic foliation, and consists of large euhedral microcline and plagioclase megacrysts (as much as 3 cm long) in a coarse- to medium-grained matrix of quartz, plagioclase, microcline, biotite, and titanite. The pluton is gray, weathers to tan, and varies in lithology from granodiorite to granite. The pluton contains numerous metamorphic amphibolitic and gneissic xenoliths. It is locally metasomatised to brick red, likely related to undated alkaline intrusions.

The Caballo granite is pink to orange, coarse- to medium-grained granite consisting of quartz, microcline, plagioclase, muscovite, biotite, iron oxides, zircon, and secondary chlorite. The Caballo granite is the largest exposure of the granitic rocks in the Caballo Mountains and extends from Burbank Canyon, southward into Apache Gap and the Red Hills (Fig. 2). The northern portion of the pluton is pegmatitic.

The Northern Caballo granite is a gray to tan, fine-grained granite consisting of quartz, microcline, plagioclase, muscovite, biotite, iron oxides, and zircon. This is the least characterized granite and additional mapping and petrographic studies are needed.

Fine-grained, typically white to light pink leucocratic granite dikes intruded the metamorphic rocks and the Longbottom Canyon pluton. They are as much as 10 m wide, 1 km long, and consist of quartz, feldspar, and trace amounts of biotite and magnetite.

A fifth pluton, the Palomas Gap granite in the Palomas Gap area is gray to pink with predominantly quartz and feldspar. This granite includes numerous inclusions of schist and amphibolite. Petrographic and major and trace element analyses are required to characterize this granite.

Possible Cambrian-Ordovician syenites, alkaline granites, and episyenites

Numerous pink to red, small stock-like to flat-lying tabular bodies and near-vertical pipes of alkaline igneous rocks intruded the Caballo granite, Longbottom Canyon pluton, Northern Caballo granite, and Palomas Gap granite in the Palomas Gap, Longbottom Canyon, Apache Gap, and the Red Hills areas of the Caballo Mountains (Fig. 2; Staatz et al., 1965; McLemore, 1986). The alkaline igneous rocks vary in lithology from syenite, monzonite, quartz syenite, and monzogranite and contain 20-50% alkali-feldspar, 20-60% plagioclase, 0-20% quartz, 1-5% opaque minerals (predominantly iron oxides), trace-5% biotite (partially to completely altered to chlorite), and trace amounts of apatite, sericite, calcite, and carbonate. Some alkali-feldspar crystals are more than a centimeter long. Plagioclase is commonly altered to carbonate, hematite, and clay and exhibits relict Carlsbad and albite twinning. Iron oxides occur as fine-grained red-brown disseminations within the feldspars, and as small red cubes, that were probably once magnetite or pyrite. In thin section, the alkaline igneous rocks are aphanitic to porphyritic and typically vesicular, with altered plagioclase phenocrysts in felty to intergranular groundmasses; the rocks are almost devoid of ferromagnesian minerals. Contacts with the host rock appear intrusive locally, but are mostly gradational as a result of metasomatism.

These alkaline igneous rocks intruded the Proterozoic granitic rocks and are unconformably overlain by the Cambrian-Ordovician Bliss Formation in the Longbottom Canyon, Apache Gap and Red Hills areas. The lower Bliss Formation in the Longbottom Canyon and Red Hills area also contains fragments of the alkaline rocks in the basal conglomeratic sandstone. Thus these alkaline rocks are older than the Bliss Formation and younger than the Proterozoic granites.

Many of these alkaline rocks are altered to brick-red, tabular bodies and pipes that consist of 85-90% red microcline with subordinate quartz, muscovite, hematite/goethite, chlorite, and trace of plagioclase with accessory apatite, zircon, calcite, fluorite, limonite, magnetite, and barite and many of the metasomatized alkaline rocks are radioactive due to high U and Th concentrations (Appendix 2; Melancon, 1952; Boyd and Wolfe, 1953; Staatz et al., 1965; McLemore, 1986). These brick-red metasomatized bodies contain as much as 14% K_2O and are best termed episyenites, indicating a metasomatic origin rather than primary igneous. Small, discontinuous pockets of uranium, thorium, and REE (rare eath elements) minerals are found locally within the episyenites and locally contain spinel, rutile, anatase, thorite, thorogummite, and uraninite. Metasomatism is very common in these occurrences, to the degree that it is sometimes difficult to determine whether the feature represents altered syenitic dike/plug or host rock that has been completely recrystallized along fractures.

MAJOR AND TRACE ELEMENT GEOCHEMISTRY

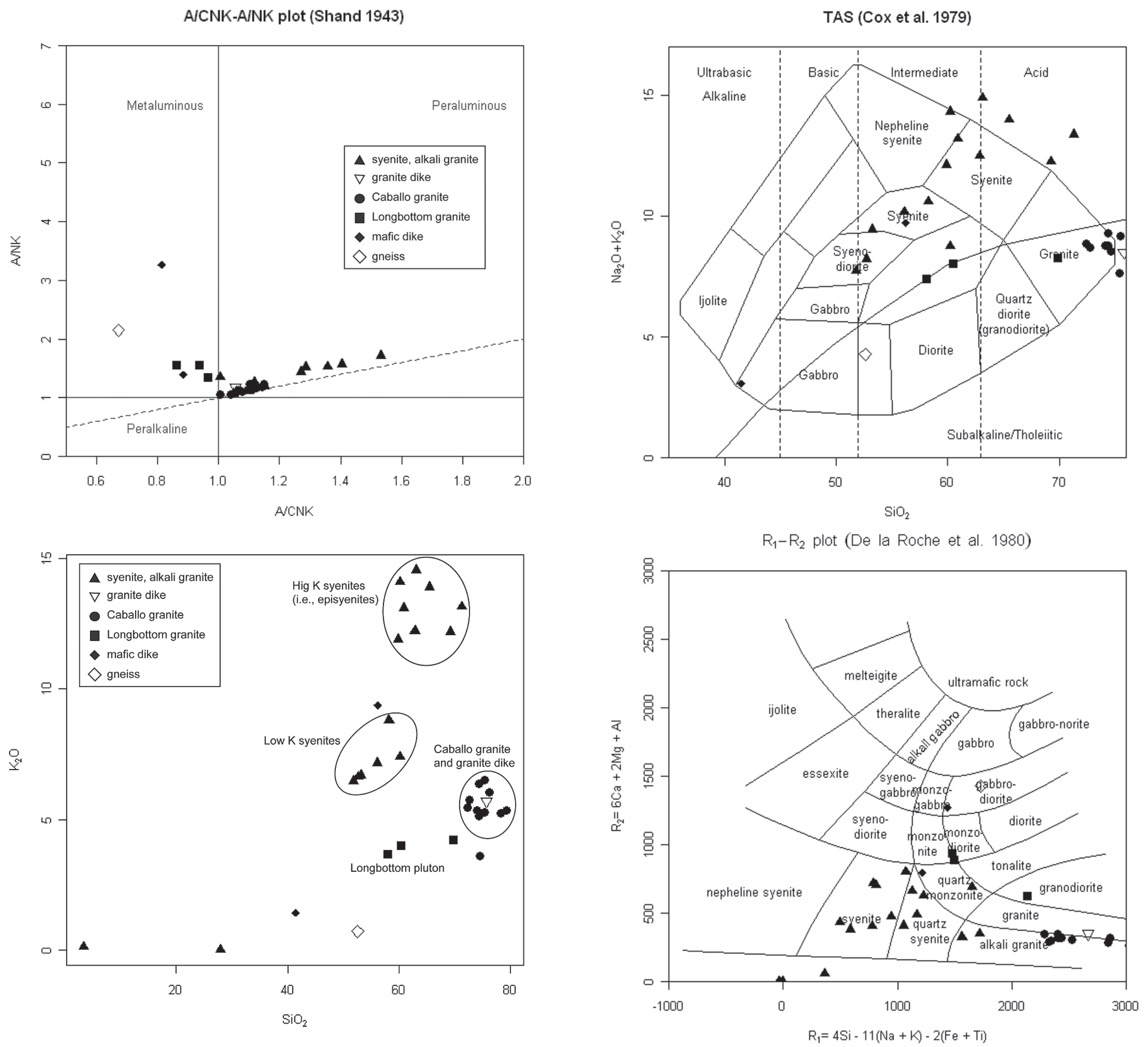
Major and trace element geochemical analyses are available for only selected samples of the basement plutonic rocks in the Caballo Mountains (Fig. 3; Appendix 1). The Longbottom Canyon pluton is metaluminous (Fig. 3a), slightly alkaline (Fig. 4b), and lower in SiO_2 than the Caballo granite (Fig. 3c, Appendix 1). The Longbottom Canyon pluton plots as granodiorite to monzodiorite on the R1-R2 plot (Fig. 3d) and differs in major and trace element chemistry from the Caballo granite and granite dike (Fig. 3; Appendix 1). The Longbottom Canyon pluton is an I- or S-type granite, according to Whalen et al. (1987).

The Caballo granite is peraluminous (Fig. 3a), subalkaline (Fig. 3b), and A-type granite (i.e., Rb/Sr>1, $K_2O/Na_2O>1$, Nb>5 ppm, V<40 ppm, and Cr<100 ppm, typical of A-type granites and the Finnish rapakivi granites; Whalen et al., 1987; Eby, 1990; Rämö, 1991).The granite dike is similar in composition to the Caballo granite (Fig. 3a,b,c,d,e). Samples of the Caballo granite and granite dike plot as granite to alkali granite on the R1-R2 plot (Fig. 3d).

The syenites, alkali granites, and monzonites in the Caballo Mountains that intruded the Proterozoic granites are alkaline (Fig. 3b) and many are metasomatic by apparent addition of K_2O (Fig. 3c) at the expense of Na_2O and CaO (McMillan and McLemore, 2004). These alkaline rocks plot as syenite, quartz syenite, and alkali granite on the R1-R2 plot (Fig. 3d). Two geochemical groups of syenites are present, a high K_2O (11-15%, metasomatic) and a low K_2O (6-7%, original) group (Fig. 3c). The unaltered Caballo syenites have higher Nb and Y than their metasomatic counterparts. The REE (rare earth elements) of the alkaline rocks are elevated (Appendix 1) and exhibit relatively flat REE patterns with a negative Eu anomaly, indicating feldspar fractionation (Fig. 3e).

GEOCHRONOLOGY

A sample of the Longbottom Canyon pluton (CAB11-6) is a brown-gray porphyritic granodiorite with large phenocrysts of microcline and plagioclase in a finer-grained matrix of quartz, plagioclase, microcline, and biotite. The biotite from CAB11-6 yields a slightly disturbed $^{40}Ar/^{39}Ar$ age spectrum and a plateau segment at 1411±3 Ma (Fig. 4a). The K-feldspar reveals an age gradient from ~1100 Ma to 800 Ma suggestive of cooling from ~250 to 175°C during this time. The Caballo granite has a U/Pb zircon age of 1487±24 Ma (Amato and Becker, 2012, this guidebook). Sample CAB11-2 from the Caballo granite has a K-feldspar with a very steeply climbing age spectrum during the first few percent of ^{39}Ar released followed by a gradual climb from ~900 to 1100 Ma (Fig. 4a). A leucocratic granite dike intruding the metamorphic complex and Longbottom Canyon pluton has a similar $^{40}Ar/^{39}Ar$ K-feldspar result and a very disturbed biotite age spectrum with a total gas age of ~1017 ± 2 Ma (Fig. 4b). The oldest ages from the spectrum are ~1300 Ma and the overall complexity of the age spectrum likely stems from chlorite alteration. The Palomas Gap granite is likely also part of the ~1480 Ma plutonic event. Sample CAB11-7 has a much younger K-feldspar



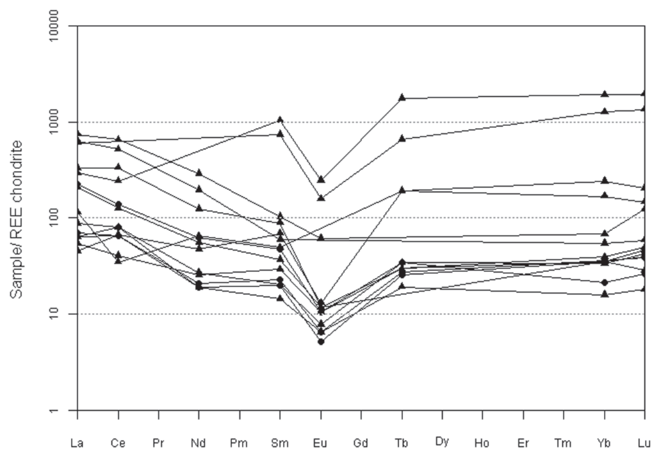


FIGURE 3. Geochemical plots of selected samples from the Caballo Mountains. Chemical analyses are in Appendix 1. Symbols are explained in 4a and 4c. (a) A/CNK-ANK plot is from Shand (1943). A/CNK (Al_2O_3/(CaO+Na_2O+K_2O) verses ANK (Al_2O_3+Na_2O+K_2O). (b) TAS plot is from Cox et al. (1979). TAS is Total alkali (NaO_2+K_2O) verses SiO_2. (c) K_2O vs. SiO_2 plot. d) R1-R2 plot from De la Roche et al. (1980). (e) Chondrite values from Nakamura (1974). Note the similarity in REE patterns between the different alkaline rocks.

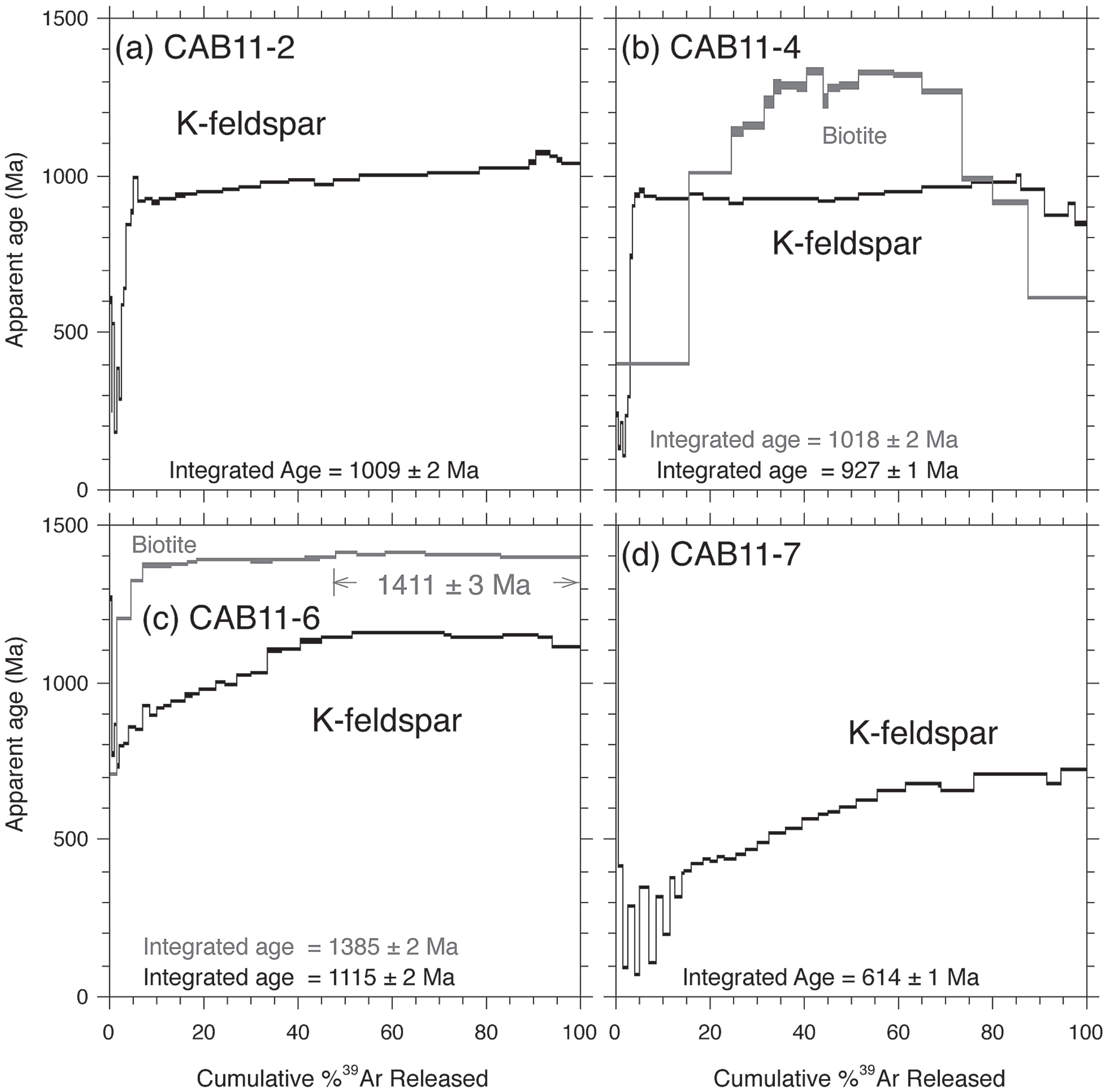


FIGURE 4. $^{40}Ar/^{39}Ar$ age spectra for granitic samples in the Caballo Mountains. Sample descriptions are in Table 3. CAB11-2 is Northern Caballo granite, CAB11-4 is granite dike, CAB11-6 is Longbottom pluton, and CAB11-7 is Palomas Gap pluton.

result compared to the other K-feldspar from the region (Fig. 5d). This spectrum has ages as young as ~70 Ma that climb to a terminal age of ~700 Ma. Either this sample has experienced cooling through ~250°C later (i.e. 700 Ma) compared to the other samples or it has been recrystallized during a ~700 Ma hydrothermal event. Detailed sample characterization is required to fully understand the significance of this K-feldspar result.

None of the alkaline igneous rocks found in the Caballo Mountains have been dated yet, but are here tentatively correlated to rocks dated elsewhere as Cambrian-Ordovician based upon similar composition, alteration, and field relationships. These rocks may correlate to well-dated alkaline rocks found in the Lobo Hill, Florida Mountains, New Mexico and McClure Mountains, Democrat Creek, and Wet Mountains in southern Colorado (Fenton and Faure, 1970; Olson et al., 1977; Armbrustmacher, 1984; Matheny et al., 1988; Evans and Clemons, 1988; McLemore et al., 1999; see references in McMillan and McLemore, 2004). Field relationships indicate that these rocks in the Caballo Mountains are older than the Cambrian-Ordovician Bliss Formation and the brick-red episyenite metasomatism is rare and distinctive only of alkaline igneous complexes. However, the granitic rocks in the Zuni and Little Hatchet Mountains, previously interpreted to be

Cambrian-Ordovician by McMillan and McLemore (2004), have since been found to be ~1000 Ma by Strikeland et al. (2003) and McLemore et al. (2012). Thus, the alkaline igneous rocks in the Caballo Mountains could be older than Cambrian-Ordovician.

ND ISOTOPE GEOCHEMISTRY

Two samples, CAB11-2 (Northern Caballo granite) and CAB11-7 (Palomas Gap granite), were analyzed for their Nd isotope composition in order to shed light on their source characteristics and to compare them to the granites of the Burro and Little Hatchet Mountains in southern New Mexico (Fig. 1; Rämö et al., 2003; McLemore et al., 2012). The two analyzed granites have high concentrations of Sm and Nd and are strongly enriched in the light REE (as shown by the low $^{147}Sm/^{144}Nd$ ratios; Fig. 5, Table 2). This is a typical feature of the Mesoproterozoic granites of southwestern New Mexico (Rämö et al., 2003). Their $^{143}Nd/^{144}Nd$ ratios also are relatively unradiogenic with corresponding εNd (at 1450 Ma) values of +2.0 (Northern Caballo granite) and +3.3 (Palomas Gap granite), and TDM model ages are on the order of ~1600 Ma.

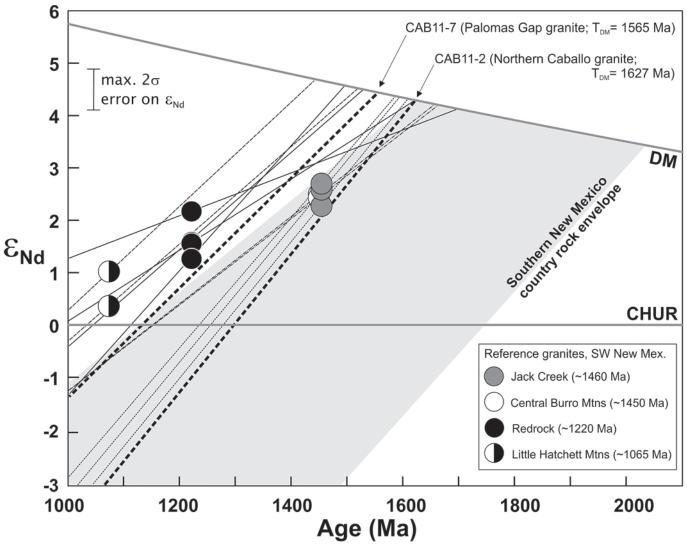


FIGURE 5. εNd vs. age diagram showing the evolution lines of the two granite samples analyzed from the Caballo Mountains (bold dashed lines). Data for the ~1450 Ma, ~1220 Ma, and ~1065 Ma granites from the Burro and Little Hatchet Mountains are also shown (Rämö et al., 2003; McLemore et al., 2012), as is a generalized evolution path for the Paleoroterozoic Mazatzal crust (Rämö et al., 2003; Amato et al., 2008; McLemore et al., 2012). DM denotes depleted mantle evolution (DePaolo, 1981). CHUR is the Chondritic Uniform Reservoir (DePaolo and Wasserburg, 1976).

MINERAL RESOURCES

Only mineral deposits that are hosted by Proterozoic metamorphic and plutonic rocks and younger, possible Cambrian-Ordovician alkaline rocks in the Caballo Mountains are briefly described in this report and include REE-Th-U veins in alkaline rocks, syenite/gabbro-hosted platinum group elements (PGE), vein and replacement deposits in Proterozoic rocks, Rio Grande Rift barite-fluorite-galena deposits, epithermal manganese deposits, and placer gold deposits. There are no active mines in the Caballo Mountains and past production from deposits in the Proterozoic and possible Cambrian-Ordovician rocks have been minor. Active mining claims cover portions of some of these deposits, and exploration and mining permits have been filed with the state.

REE-Th-U veins in alkaline rocks

McLemore (1986), McLemore et al. (1988a, b) and Long et al. (2010) briefly described the known REE-Th-U and Nb veins and episyenite deposits in the Red Hills area of the Caballo Mountains. Additional areas are found in the Palomas Gap, Longbottom Canyon, and Apache Gap of the Caballo Mountains (Fig. 2; mapping by the senior author). The veins are spotty, discontinuous tabular bodies, narrow lenses, and breccia zones along faults, fractures, and shear zones in syenites, monzonites, quartz syenites, and monzogranites and contain local high concentrations of REE, niobium, thorium, and uranium (Staatz et al., 1965; McLemore, 1986). Selected samples of veins from the Red Hills area in the Caballo Mountains contain as much as 20,000 ppm Th, 1,600 ppm U, 500 ppm Nb, 5,000 ppm Y, 600 ppm Be, 7,500 ppm Ga, and 200 ppm La (Appendix 2). Mining claims have been staked on these deposits in several areas in the Caballo Mountains. More research is underway on these deposits by the authors.

Proterozoic syenite/gabbro-hosted platinum group elements (PGE) deposits

Platinum group elements (PGE) typically occur in economic concentrations in ultramafic and associated mafic rocks (Eckstrand, 1984; Cox and Singer, 1986; Macdonald, 1988) and the Proterozoic gabbro/amphibolites in the Longbottom Canyon area have been exploited for potential PGE. PGE includes platinum, palladium, osmium, ruthenium, iridium, and rhodium. The average concentration of platinum in unmineralized mafic and ultramafic rocks is approximately 10 ppb, ranging from 0.1 to 500 ppb (Mcdonald, 1988). Combined PGE content of most ore deposits ranges from 1 to 20 ppm (Eckstrand, 1984). PGE ore occurs as conformable layers or lenses near the base of layered ultramafic and mafic complexes, thin stratiform layers, and irregular pipe-like bodies within ultramafic and mafic complexes. None of these features were found in the Caballo amphibolites that are typically fine-grained and massive. A processing plant was built south of Longbottom Canyon in the 1990s to potentially recover PGE and Au, but was unsuccessful. Some concentrate was reportedly shipped to a plant in the Midwest, but recovery was still unsuccessful. The Proterozoic amphibolites (gabbro) from the Caballo Mountains contained only 1-3 ppb Pt and 1-2 ppb Pd (Appendix 2). Adjacent granitic rocks (also processed at the plant) contained no detectable PGE. Similar Proterozoic gabbro/amphibolite from the Sacramento Mountains contained 1 ppb Pt and 66 ppb Pd (New Mexico Bureau of Mines and Mineral Resources et al., 1998). There are no PGE proved reserves or ore deposits known in New Mexico that contain high enough concentrations of significant volume to be mined economically for PGE, including the mafic rocks in the Caballo Mountains (McLemore et al., 1989).

Vein and replacement deposits in Proterozoic rocks

Vein and replacement deposits are found scattered throughout the Proterozoic rocks in the Caballo Mountains. Several thin, lenticular, Cu-Ag-Au quartz veins along shear zones cut Proterozoic granite throughout the Caballo Mountains. Malachite, iron oxides, azurite, calcite, and quartz are the predominant minerals. Bornite, cuprite, chalcopyrite, chalcocite, and other copper minerals occur in small ore shoots within some veins. The veins occur along faults, which typically strike N80°W to N80°E and are steeply dipping. The age of mineralization is uncertain and presumed Proterozoic, since some veins hosted by Proterozoic granite are unconformably overlain by the Cambrian-Bliss Formation. Metals production is unknown. Concentrate samples from the PGE-Au plant did contain 77,600 ppb Au (Appendix 2); but samples of veins and shear zones in the Proterozoic Caballo granite were typically low, less than 360 ppb Au (Appendix 2). Although, there are active mining claims, most of these precious-base-metal vein deposits in the Caballo Mountains are small and low grade.

Rio Grande Rift barite-fluorite-galena deposits

Numerous Rio Grande Rift barite-fluorite-galena deposits are found in Proterozoic and Paleozoic rocks in the Caballo Mountains. High-angle, normal faults, related to the Rio Grande Rift, host most of the deposits in the Proterozoic rocks in the Caballo Mountains. Rio Grande Rift barite-fluorite-galena (±silver, copper) (RGR) deposits are low-temperature, open-space fillings with little or no replacement of secondary minerals and are not obviously associated with any magmatic activity (McLemore and Barker, 1985; McLemore and Lueth, 1996; McLemore et al, 1998; Lueth et al., 2004; 2005; Partey et al., 2009) and were formerly called sedimentary-hydrothermal deposits (North and McLemore, 1986, 1988). RGR deposits occur along faults, fractures, contact zones, shear zones, bedding planes, and solution cavities in Proterozoic granitic rocks in the Caballo Mountains. Widths range up to several meters and some deposits can be traced along strike for several hundred meters. The age of the mineralization is uncertain, but work in central and southern New Mexico suggests they could be as old as late Miocene or as young as Pliocene (McLemore and Barker, 1985; North and McLemore, 1985; Lueth et al., 1998; Lueth et al., 2004, 2005; Partey et al., 2009). Most RGR deposits in New Mexico are small, typically less than a few thousand metric tons of ore and uneconomic.

Epithermal manganese deposits

Epithermal manganese deposits occur as fracture coatings, breccia cement, and veins along fracture and fault zones in Proterozoic granite in the Caballo Mountains. In the Caballo Mountains, many manganese deposits also contain fluorite; but in the Rincon mining district in the southern Caballo Mountains (McLemore, 2012, this guidebook) many manganese deposits contain barite. These deposits are too small and low grade to be economic.

Placer gold deposits

Placer gold deposits are found in many arroyos draining the Proterozoic rocks in the Caballo Mountains. During fluvial events, large volumes of sediment containing free gold are transported and deposited in relatively poorly-sorted alluvial and stream deposits. The gold concentrates by gravity in incised stream valleys and alluvial fans in deeply weathered highlands. The deposits were probably derived from quartz veins, pegmatites, and replacement deposits in Proterozoic granite and Au-bearing jasperoids in the Paleozoic limestones. Native gold and electrum occurs with quartz, magnetite, ilmenite, amphiboles, pyroxenes, pyrite, zircon, garnet, rutile, and a variety of other heavy minerals. The gold is typically fine-grain size, contains traces of silver, and has a coarse, rough texture, indicating a short distance of transport. Samples from a bulldozer pit in Granite Canyon contained as much as 85 ppb Au (Appendix 2). The best gold values occur near the base of alluvial gravel deposits where the gold is trapped by natural processes such as riffles in the river bottom, fractures within the bedrock, along bedding or foliation planes, and/or structures that are transverse to the river flow. Gold also concentrates above cemented gravels and clay layers within gravel deposits, which constrain downward migration of gold particles. Most deposits are thin. The placer deposits in the Caballo Mountains are too small and low-grade to be economic except for small gold-panning operations.

DISCUSSION AND PRELIMINARY CONCLUSIONS

The southwestern boundary of the Laurentia continent is not well constrained because of small outcrop areas (Fig. 1) and, in many areas, intense alteration. However, new ages of plutonic and metamorphic rocks in the Caballo Mountains indicate a significant period of ~1480 Ma magmatism followed by protracted cooling to ~250°C by 1100 Ma. Amato and Becker (2012, this guidebook) demonstrate that the Caballo Mountains are dominated by ~1480 Ma intrusions and our Nd isotopic data comply with this (Table 2). $^{40}Ar/^{39}Ar$ dating of biotite and K-feldspar (Fig. 4; Appendix 2) indicate overall protracted cooling to ~250°C by ~1100 Ma and are consistent with other argon data from New Mexico rift-flank uplifts (Sanders et al., 2006; Karlstrom et al., 1997; Marcoline et al., 1999). Alkaline magmatism occurs in the Caballo Mountains and may be associated with regional Cambrian-Ordovician magmatic episodes, but no direct radiometric dating has yet identified intrusions of this age in the Caballo Mountains. The earliest known magmatic event in the Caballo Mountains occurred during the Mazatzal event with intrusion of ~1680 Ma gneissic granite (Amato and Becker, 2012, this guidebook) into metamorphic rocks of similar in age to gabbroic and granitic rocks found in the Burro Mountains (~1630 Ma, Rämö et al., 2003; Amato et al., 2011), San Andres Mountains (~1630-

1675 Ma, Amato et al., 2008), Florida Mountains (~1623 Ma, Amato et al., 2008), and Kingston (~1654 Ma, Amato and Becker, 2012, this guidebook). The Caballo granitic plutons are part of the widespread ~1480 Ma Laurentian Mesoproterozoic granite-rhyolite belt that are found throughout New Mexico. A summary of the events in the Caballo Mountains is in Table 3.

Nd isotope data on Proterozoic granites of southwestern New Mexico are available for three groups of plutons emplaced at ~1460 Ma, ~1220 Ma, and ~1065 Ma (Rämö et al., 2003; McLemore et al., 2012). Their Nd isotope compositions are illustrated with the Caballo samples in an eNd vs. Age diagram in Figure 5. Overall, there is a time-associated evolution of available initial values from about +2.5 to +0.5 in 400 m.y. (from ~1480 to ~1100 Ma). This trend deviates from the evolution path of the surrounding (Mazatzal) crust (Fig. 5) and implies an increasing juvenile source component in the granites through time (Heinonen et al., 2011). Lack of U-Pb dates for the Northern Caballo and Palomas Gap granites precludes the comparison of their initial εNd values, but the Nd isotope evolution lines of the two samples from the Caballo Mountains are similar to the evolution (and TDM values) of the ~1480 Ma group. This implies that the Caballo granites have a ~1600 Ma crustal source similar to the Burro Mountain granites (i.e. Rämö et al., 2003) and would rather belong to the regional ~1480 Ma granite group than the younger granites with relatively more juvenile Nd isotope signatures. U-Pb zircon data by Amato and Becker (2012, this guidebook) on the Longbottom Canyon pluton (Table 1) further imply that the Caballo Mountains host 1480-1340 Ma granites. Detailed geologic mapping of the Proterozoic and possible Cambrian-Ordovician rocks is required in the Caballo Mountains to understand the field relationships. The U-Pb zircon and Nd isotopic data indicate that some of the Caballo granites are ~1480 Ma and other thermal events reset the ages of the granitic rocks. K-feldspar thermochronology indicates significant exhumation beginning at ~1100 Ma that likely reflects Grenville-aged compression. Younger K-feldspar ages (~700 Ma) may record an event of metasomatic alteration. Additional detailed mapping and analyses (major and trace element analyses, isotopic analyses, and dating) of the Proterozoic and possible Cambrian-Ordovician rocks is required in the Caballo Mountains to test this hypothesis, to identify possible heat sources for the younger ages, and to better understand the field relationships of all the rock types.

A variety of mineral deposits are found in these Proterozoic and possible Cambrian-Ordovician rocks in the Caballo Mountains, but most of these mineral deposits are small, low grade, and uneconomic. Many REE-U-Th vein deposits associated with Cambrian-Ordovician alkaline magmatism in New Mexico and southern Colorado were first examined for their U potential in the 1950s and subsequent studies have found that these deposits also include anomalous concentrations of Th, REE, Nb, Ga, Zr, Hf, and Y (McLemore et al., 1988a, b; Long et al. 2010). However, only a few of these alkaline deposits have been examined in detail (McLemore, 1983; Ervin, 1998; McLemore et al., 1999; McMillan and McLemore, 2004), and therefore the potential economic significance of these deposits cannot be fully assessed at this time. Additional detailed mapping, petrographic, mineralogical, and geochemical analyses are required to adequately assess the economic potential of these deposits, as well as determine their origin and tectonic setting (i.e. regional metallogenic framework), and determine the economic potential for additional undiscovered REE-U-Th vein deposits. Only the gold veins in Proterozoic rocks, placer gold deposits, and REE-U-Th veins in possible Cambrian-Ordovician alkaline igneous rocks and associated metasomatic episyenites have future potential.

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TABLE 3. Summary of sequence of events in the Caballo Mountains during the Proterozoic and Cambrian-Ordovician.

Event	Age	Event
syenites/alkali granites/episyenites	<700 Ma	Possible Cambrian-Ordovician aulacogen or older
Palomas Gap granite	Minimum 700 Ma, but likely ~1450 Ma	~1450 Ma granite-rhyolite event
granite dikes	minimum 1010 Ma, but likely ~1450 Ma	~1450 Ma granite-rhyolite event
Longbottom Canyon pluton	~1486 Ma	~1450 Ma granite-rhyolite event
Caballo granite	~1487 Ma	~1450 Ma granite-rhyolite event
gneissic granite	~1681 Ma	Mazatzal orogeny
volcanic felsic eruptions	>1681 Ma	Mazatzal orogeny
basaltic flows/sills	>1681 Ma	Mazatzal orogeny

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George Koepke working his prospect near Cuchillo, ca 1947. NMBGMR Photo Archive No. p-00669B