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CHARACTERIZATION AND ORIGIN OF EPISYENITES IN THE SOUTHERN CABALLO MOUNTAINS, SIERRA COUNTY, NEW MEXICO

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Abstract—Brick-red, K-feldspar-rich rocks, called episyenites (altered rocks that were desilicated and metasomatized by alkali-rich solutions) are found in several areas in southern and central New Mexico. These rocks contain anomalous concentrations of rare earth elements (REE, <2329 ppm), uranium (U, <9721 ppm), thorium (Th, <1378 ppm), niobium (Nb, <247 ppm) and high heavy REE (<133 ppm Yb and <179 ppm Dy). In the Caballo Mountains, the timing of metasomatism is older than late Cambrian as episyenite clasts occur in the Cambrian-Ordovician Bliss Formation that unconformably overlies episyenites and Proterozoic host rocks. $^{40}Ar/^{39}Ar$ dating of K-feldspars within the episyenites yields complex and intriguing age results that are likely related to multiple fluid-alteration events possibly during the Ancestral Rocky Mountains and Laramide orogenies. Rare U, Th, Nb, and REE minerals are found in the Caballo episyenites and could indicate potential REE mineralization at depth, including heavy REE. Synchysite is a major host of light REEs in the episyenites, while heavy REEs are concentrated predominantly in xenotime and priorite. Textural evidence and field relationships indicates that REE-bearing phases co-precipitated during metasomatism prior to deposition of the Cambrian-Ordovician Bliss Formation. The maximum age of the metasomatism forming the episyenites is between the age of the host granite (~1400 Ma) and the Bliss Formation (late Cambrian-early Ordovician). The K-feldspars in the episyenites were then re-heated during the Ancestral Rocky Mountains and Laramide orogenies.

INTRODUCTION

Brick-red, K-feldspar-rich rocks, called episyenites, were first found in southern New Mexico in the 1950s during exploration for uranium deposits (Fig. 1; Staatz, et al., 1965; McLemore, 1986). Some of these complexes in New Mexico and elsewhere are known for potential economic deposits of rare earth elements (REE), uranium (U), thorium (Th), niobium (Nb), and other elements (Long et al., 2010; McLemore, 2015). Rare earth elements (REE) and other critical elements are increasingly becoming more important in our technological society. Because of the chemical and physical properties of REE, they are used in many diverse defense, energy, industrial, and military applications, like cell phones, computers, magnets, batteries, solar panels, and wind turbines (Long et al., 2010). Because of this importance, the authors mapped and sampled these unusual metasomatic rocks, with the goals of better understanding their tectonic setting, mechanisms of origin, and to evaluate their economic potential. Similar episyenites and fenites are found elsewhere in New Mexico and southern Colorado (Fig. 1) and are thought to be part of a Cambrian-Ordovician alkaline magmatic event that is documented throughout southern Colorado and New Mexico (Armbrustmacher, 1984; McMillan and McLemore, 2004; Riggins et al., 2014; McLemore, 2016; McLemore and Lueth, 2017). However, new age dating of the Caballo episyenites yields complex and intriguing age results that are likely related to multiple fluid-alteration events of different ages, and there is no geochronological evidence to support a relationship to the Cambrian–Ordovician alkaline magmatic event in the Caballo Mountain.

DEFINITION OF EPISYENITES

The term *episyenite* is used to describe altered rocks that were desilicified (subsolidus dissolution of quartz) and metasomatized by alkali-rich fluids (Leroy, 1978; Recio et al., 1997). The metasomatic rocks in several areas in New Mexico, including the Caballo, Burro, and Zuni Mountains, Sevilleta Wildlife Refuge, and Lobo Hill (Fig. 1), were erroneously called syenites and alkali granites (Condie and Budding, 1979; McMillan and McLemore, 2004) but are actually metasomatic in origin and not primary igneous rocks (McLemore, 2013, 2016; Riggins, 2014; Riggins et al., 2014; Smith, 2018). Elsewhere in the world, these alkali-rich metasomatic rocks are associated with uranium and thorium deposits (Costi et al., 2002; Condomines et al., 2007; Cuney et al., 2012), gold deposits (López-Moro et al., 2013) and tin–tungsten deposits (Charoy and Pollard, 1989; Costi et al., 2002; Borges et al., 2009), but many unmineralized episyenites are found as well (Petersson and Eliasson, 1997; Recio et al., 1997; Hecht et al., 1999; Nishimoto et al., 2014). Episyenites are similar to altered rocks formed by fenitization and would be called fenites by some geologists. Fenitization is the alkali-metasomatism associated with carbonatites or alkaline igneous activity (Le Bas, 2008). However, we are reluctant to use the term fenite for these rocks studied here because there is no definitive spatial association with carbonatite or alkaline igneous rocks. Despite numerous studies on episyenites, the origin and mechanism of the formation of these potentially REE-, U-, Th- and Nd-enriched rocks is unknown. This report summarizes results and interpretations of on-going mapping, geochemical, and geochronological studies.

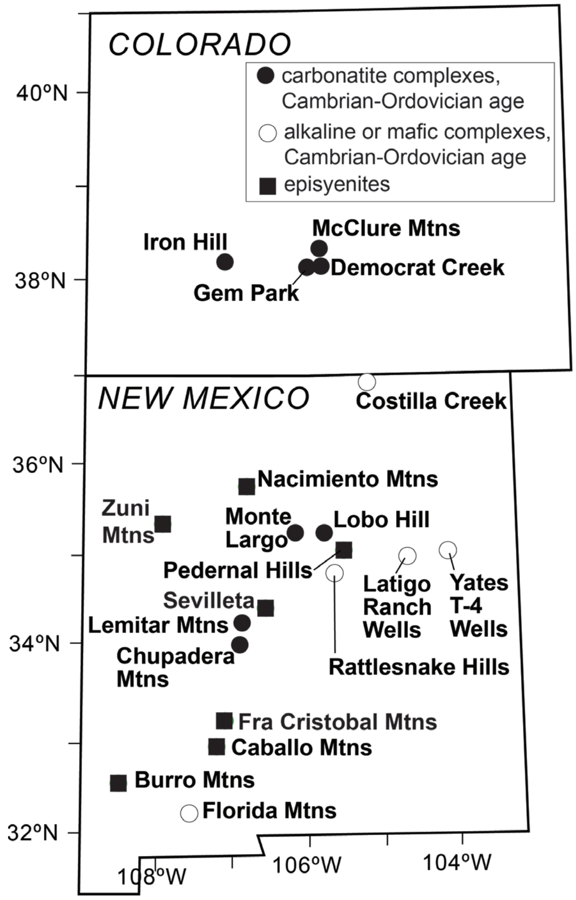

FIGURE 1. Locations of areas with episyenites in New Mexico.

PREVIOUS WORK

In the 1950s, prospectors located several areas of anomalously high radioactivity in the Caballo Mountains and attributed it to the presence of uranium. Shallow prospect pits and adits were dug and holes drilled on many of the claims in the area (Appendix 1); but, assay results were low and the claims were later dropped with no production. Radioactive syenite dikes were reported in the southern Red Hills in the Caballo Mountains by Melancon (1952) and Boyd and Wolfe (1953) during a reconnaissance for uranium deposits. The radioactive deposits in the southern Red Hills were subsequently studied in more detail by Staatz et al. (1965) and McLemore (1986). In 2012, the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) began more detailed examination of these unusual rocks; Riggins (2014) and Riggins et al. (2014) presented preliminary results of that research. Smith (2018) continued to examine these rocks. Recently, mining claims and surface sampling of some of these bodies have been undertaken by prospectors looking for REE.

METHODOLOGY

Field investigations of the metamorphic and plutonic rocks in the Caballo Mountains by the senior author began in 1980 in order to assess their economic potential and tectonic setting (McLemore, 1986). Continued examinations occurred in 1995–1996, as part of the evaluation of mineral resources in the Caballo resource area in Sierra and Otero Counties (Green and O'Neill, 1998). In 2012–2017, more detailed investigations were carried out.

Published and unpublished data were compiled and examined. Mineral occurrences, deposits, mines, and prospects were identified, plotted on base maps, described in detail (Appendix 1), and compiled in the New Mexico Mines Database. Detailed field mapping at scales of 1:6,000 to 1:12,000 were compiled in ARCMAP@ using U.S. Geological Survey (USGS) topographic maps as the map base (Figs. 2, 3, 4). Color versions of the geologic maps are in Appendix 2 along with color photographs of episyenites. The mapping in 2012–2017 is more accurate than previous mapping because a handheld GPS unit was used with the current topography loaded in the unit.

Selected samples of the Proterozoic host rocks and episyenites were collected and analyzed by a variety of methods. Rock samples collected during 1985 were analyzed for major and trace elements by X-ray fluorescence (XRF) at the NMBGMR XRF laboratory, on a PW 2400 instrument using standard instrument settings on fused glass discs and trace elements using pressed powder briquettes. Mineralized samples collected for the USGS Caballo project in 1995–1996 were submitted to the USGS for analyses by Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES) and INAA. Additional analyses of the igneous and metasomatic rocks collected in 2012–2017 were by XRF and ICP by Activation Laboratories, methods for which can be found at www.actlabs.com. Mineralogy of selected samples was determined by X-ray diffraction (XRD). Locations of samples and whole-rock geochemical analyses are in Appendix 3.

Selected samples of episyenite and granitic host rocks were investigated using a Cameca SX100 electron microprobe at NMBGMR to characterize compositional, chemical and textural characteristics of host granite and episyenite. Episyenite samples chosen for microprobe analysis were selected based on two criteria: 1) elevated whole-rock concentrations of U, Th, and REE, and 2) texture and relationship with the granitic host rock. Samples of granitic host rocks were selected from areas known to have undergone minimal alteration, and are therefore representative of original host rock compositions and textures. More details on the analytical procedures are by Riggins (2014) and Smith (2018).

Selected K-feldspar samples of episyenite were dated by furnace incremental heating $^{40}Ar/^{39}Ar$ age spectrum method by the New Mexico Geochronological Research Laboratory (NMGRL) at NMBGMR. Samples of granitic host rock were also dated to provide a baseline of K-feldspar age behavior for the area. Samples were crushed and sieved, and K-feldspars were hand-picked under a binocular microscope. An effort was made to avoid picking K-feldspars that were obviously zoned, contained inclusions, or had attached fragments of other minerals. Grains were washed with deionized water in a sonic bath to remove fine-grained particulates and dried at room temperature, before being loaded into aluminum discs for irradiation. Samples were irradiated at the USGS TRIGA reactor in Denver, CO for 40 hours. Fish Canyon 2 sanidine was used to monitor neu-

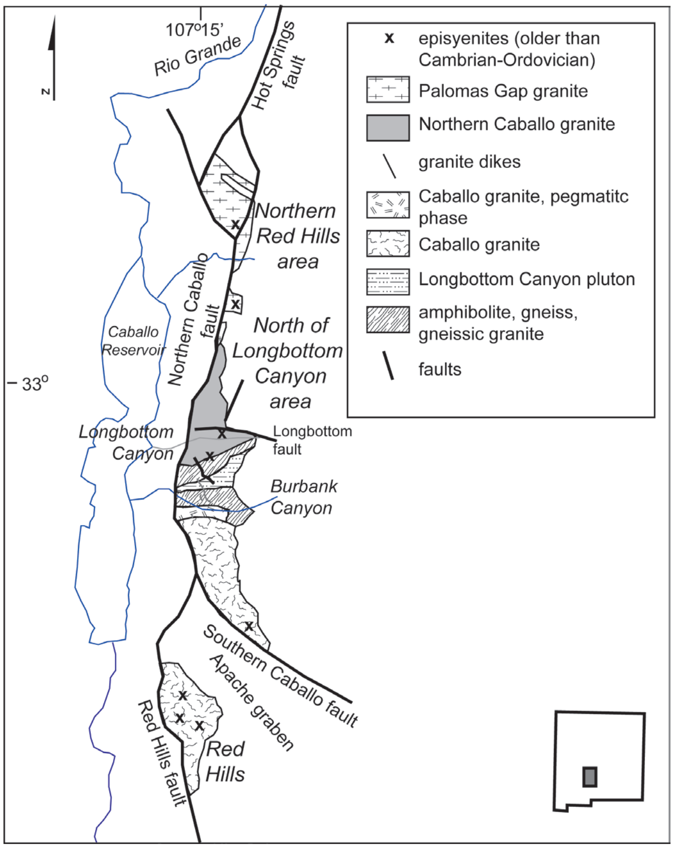

FIGURE 2. Simplified geologic map of Proterozoic rocks and Cambrian-Ordovician episyenites of the Caballo Mountains, New Mexico (modified from Condie and Budding, 1979; Seager and Mack, 2003; McLemore et al., 2012).

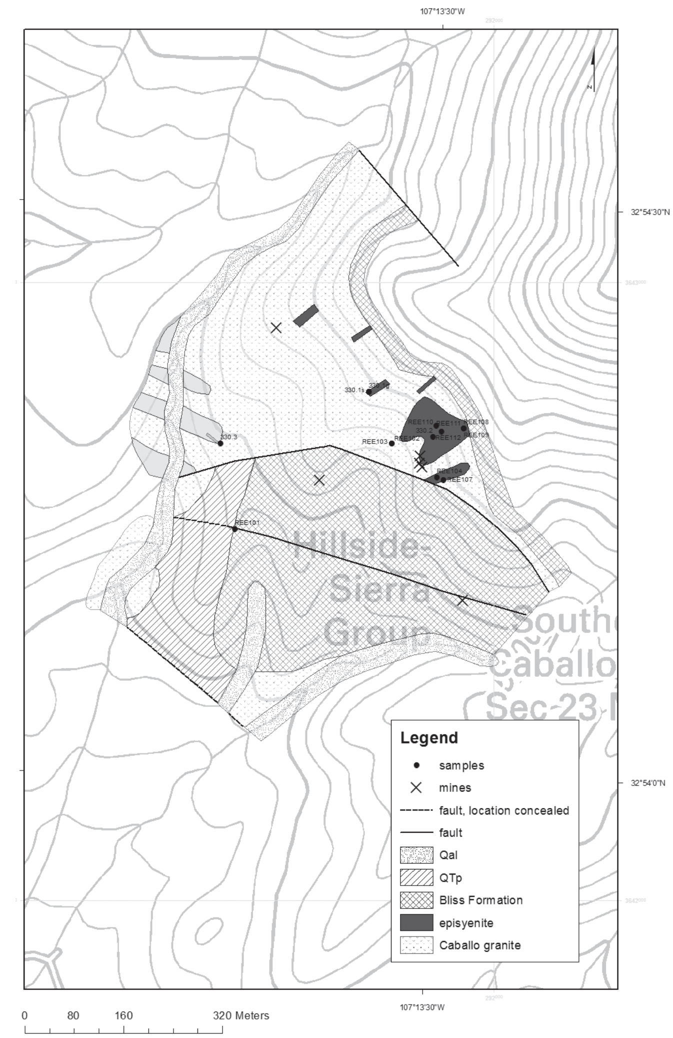

FIGURE 3. Geologic map of the Apache Gap episyenites area, southern Caballo Mountains.

tron flux, with an assigned age of 28.204 Ma. After irradiation, single K-feldspar crystals were loaded into copper trays and placed under vacuum. Crystals were step-heated with a 50W CO_2 laser and analyzed by the NMGRL Mass Analyzer Products 215-50 mass spectrometer or step-heated with the NMGRL sample furnace and analyzed with the Helix MC Plus multicollector mass spectrometer. More detailed laboratory methods are described at http://geoinfo.nmt.edu/labs/argon/home.html and in Riggins (2014) and Smith (2018).

GEOLOGY OF CABALLO MOUNTAINS

The Caballo Mountains are an east-dipping fault block along the eastern Rio Grande Rift in central New Mexico (Fig. 2) and are comprised of rocks ranging in age from Proterozoic to Recent. The Proterozoic rocks in the Caballo Mountains have been mapped by Kelley and Silver (1952), Staatz et al. (1965), Condie and Budding (1979), Bauer and Lozinsky (1986), McLemore (1986), and Seager and Mack (1991, 2003, 2005). Proterozoic plutonic rocks form the lower slopes of the Caballo Mountains and include at least four different granitic bodies (Caballo granite, Longbottom granite/granodiorite pluton, Northern Caballo granite, Palomas Gap pluton) that are intruded by pegmatite, granite, and aplite dikes. Age dates are summarized in Table 1.

The oldest rocks in the Caballo Mountains are ~1680 Ma metamorphosed amphibolites, quartz-feldspathic schist (paragneiss), felsic gneiss, and granitic gneiss (orthogneiss) exposed in the Longbottom and Burbank Canyons (Condie and Budding, 1979; Bauer and Lozinsky, 1986; McLemore, 1986, Seager and Mack, 2003, 2005; Amato and Becker, 2012; McLemore et al., 2012). The ~1486 Ma Longbottom Canyon pluton intruded the metamorphic complex (Seager and Mack, 2003; Amato and Becker, 2012), is concordant with metamorphic foliation, and consists of large euhedral microcline and plagioclase megacrysts (as much as 3 cm long) in a 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.

The ~1487 Ma Caballo granite forms the largest exposure of the granitic rocks in the Caballo Mountains and extends from Burbank Canyon, southward into Apache Gap and the Southern Red Hills (Fig. 2; Seager and Mack, 2003; Amato and Becker, 2012; McLemore et al., 2012). The northern portion of the pluton is pegmatitic in texture. The Caballo granite is pink to orange- to buff-colored, medium- to coarse-grained granite consisting of nearly equal amounts of quartz, microcline, and

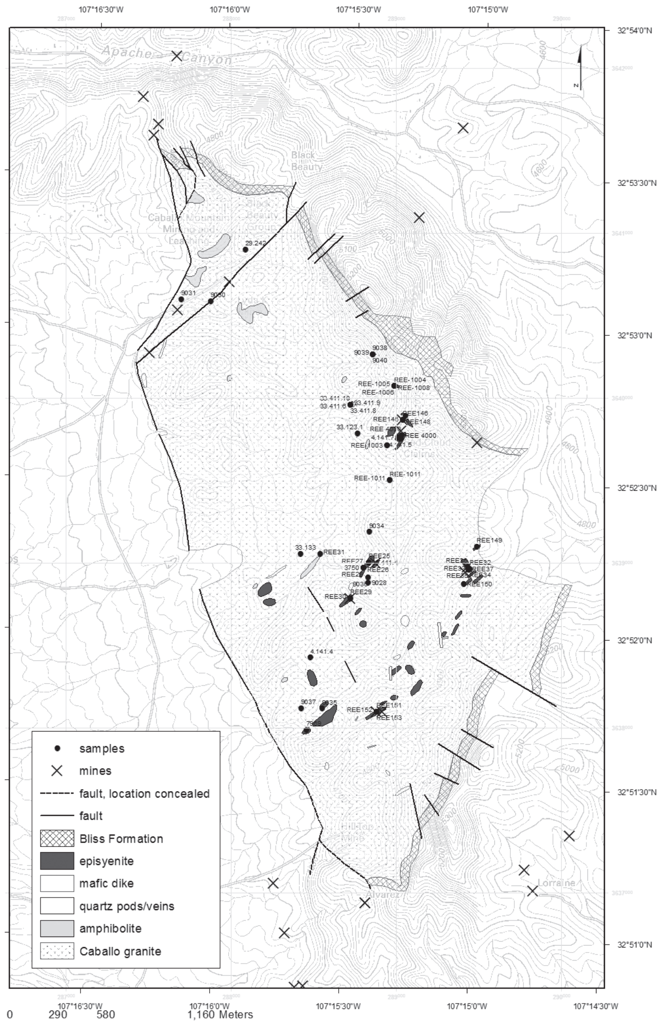

FIGURE 4. Geologic map of the Southern Red Hills episyenites area, southern Caballo Mountains.

plagioclase, with accessory biotite, iron oxides, hornblende, titanite, zircon, and secondary chlorite and epidote. Numerous xenoliths or lenses of granitic schists, black amphibolite, and pink felsic orthogneiss are found within the Caballo granite. Biotite is the most abundant mafic mineral, with hornblende, titanite, iron oxides, and epidote as accessory minerals. Amato and Becker (2012) dated the Caballo granite as 1487±24 Ma (U/Pb).

The Northern Caballo granite is defined by Seager and Mack (2003) and McLemore et al. (2012) 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 Northern Caballo granite is a gray to tan, fine-grained granite consisting of nearly equal amounts of quartz, microcline, and plagioclase, with accessory muscovite, biotite, iron oxides, and zircon. This is the least-characterized granite and additional mapping and petrographic studies are needed.

A fourth pluton, the Palomas Gap granite 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). The Palomas Gap granite is gray to pink with predominantly quartz and feldspar. This granite includes numerous inclusions of schist and amphibolite.

Pegmatite, granite, and aplite dikes intruded the metamorphic and granitic rocks. They are as much as 10 m wide, 1 km long and consist of quartz, feldspar, and trace amounts of biotite and magnetite. Pegmatite dikes are pink to white, coarse-grained, simple, unzoned quartz–feldspar pegmatites. Some pegmatites grade into white quartz veins. The granite dikes are fine- to medium-grained, typically white to light pink leucocratic granite. Aplite dikes are pink, fine-grained granitic dikes that locally grade into pegmatite dikes.

Brick-red to red to orange, fine- to coarse-grained, K-feldspar-rich episyenites are found in several areas in the Proterozoic terrain in the Caballo Mountains (Fig. 2). The brick-red color is the result of pervasive hematitization, resulting from small hematite inclusions within the feldspar crystals (McLemore, 1986; Smith, 2018). Most episyenites are radioactive (more than three times background radioactivity). Most of the contacts between the episyenites and host rocks are either: 1) diffuse, irregular, and gradational or 2) sharp. The contacts are marked by a color change from orange or pink of the host rock to darker pink to brick red (Appendix 2). The Proterozoic rocks and the episyenites are unconformably overlain by the Cambrian–Ordovician Bliss Formation in several localities in the Caballo Mountains, indicating that they should be Cambrian–Ordovician or older in age.

In addition to episyenites, abundant, but small and uneconomic mineral deposits are found in the Caballo Mountains that are evidence of multiple periods of fluid movement throughout geologic time that could have reset the age dates. Proterozoic amphibolites (gabbro) from the Longbottom Canyon contained 1–3 ppb Pt and 1–2 ppb Pd and could be indicative of syenite/gabbro-hosted platinum group elements deposits (McLemore et al., 2012; McLemore and Lueth, 2017). Vein and replacement deposits are found scattered throughout the Proterozoic rocks in the Caballo Mountains, but the age of these deposits are uncertain. Cambrian–Ordovician sedimentary iron deposits are found the Caballo Mountains, where oolitic hematite was mined from two zones in sandstones of the Cambrian–Ordovician Bliss Formation (Kelley, 1949; McLemore and Lueth, 2017). Numerous jasperoid zones have replaced limestones of various ages (Kelley and Silver, 1952; Seager and Mack, 2003; V.T. McLemore, unpubl. mapping and sampling) and could have formed during the Ancestral Rock Mountain orogeny or Rio Grande rift. Mineral deposits found in the Caballo Mountains that likely formed during the extension of the Rio Grande rift include 1) copper-silver vein deposits southwest of Palomas Gap, 2) Rio Grande Rift barite–fluorite–galena deposits, 3) epithermal manganese deposits, and 4) placer gold deposits (McLemore et al., 2012; McLemore and Lueth, 2017).

DESCRIPTION OF EPISYENITES IN THE SOUTHERN CABALLO MOUNTAINS

Apache Gap

Brick red episyenites are found in a fault block in the Apache Gap area, near the base of the Caballo Mountains (Fig.

TABLE 1. Summary of ages of Proterozoic granites and younger episyenites from the Caballo Mountains (UTM coordinates are NAD 27, Zone 13; locations in parenthesis are from Amato and Becker, 2012). Geologic units are defined by Condie and Budding (1979), Seager and Mack (2003), and McLemore et al. (2012). std dev- standard deviation.

Sample	Latitude (decimal degrees)	Longitude (decimal degrees)	Geologic Unit	Description	Integrated $^{40}Ar/^{39}Ar$ Age (K-feldspar) Ma (McLemore et al., 2012; Smith, 2018)	Integrated $^{40}Ar/^{39}Ar$ Age (biotite) Ma (McLemore et al., 2012; Smith, 2018)	U-Pb ages (Amato and Becker, 2012)
CAB11-7	33.049636	107.230396	Palomas Gap granite	gray to pink granite, with quartz, feldspar	609.1±1.0		
CAB11-4	32.94469	107.254995	granite dike	white granite dike cutting Caballo granite containing quartz, feldspar, biotite	919±1.3	1010.6±1.6	
CAB11-2	32.977427	107.247333	Northern Caballo granite	gray to tan, fine grained granite	1001.2±1.5		
06CM-01	32.943815	107.258513	Caballo granite				1487±24
CAB11-6, 06CM-01	32.959758	107.255506	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
06CM-02	32.960427	107.261877	gneissic granite				1681±12
REE-1004	32.880238	107.255502	Caballo granite	equigranular aplite dike of Caballo granite, partially chloritized	1017.8±1.1 (average of 3 analyses)	1354.33±0.64	
REE-1005	32.880238	107.255502	Caballo granite	Coarse grained granite with fully chloritized biotite, small (<1 cm long) megacrysts of K-feldspar, plagioclase and quartz	998.1±3.5 (average of 3 analyses)		
REE-1003	32.876984	107.255901	Episyenite (S. Red Hills)	Nearly completely altered episyenite with brick-red feldspar, chlorite (±vermiculite?) bearing, LREE enriched	404.4±2.6 (std. dev: 37.1) (average of 11 analyses)		
REE-1007	32.880238	107.255502	Episyenite (S. Red Hills)	nearly completely altered episyenite, brick red K-feldspar, contains chlorite and fluorite, xenotime	394.5±2.0 (std. dev: 42.3) (average of 12 analyses)		
REE-1009	32.880238	107.255502	Episyenite (S. Red Hills)	pale pink, partially altered pegmatite, original graphic quartz texture destroyed	417.8±1.0 (std dev: 17.9) (average of 3 analyses)		

3). The episyenites are within the Caballo granite, steeply dipping lens-shaped bodies, and consist of coarse- to fine-grained K-feldspar and lesser amounts of disseminated quartz, hematite, and chlorite. The coarse-grained zones resemble the textures of unaltered pegmatite dikes. One episyenite body is 76 m wide and 123 m long and another body is 91 m long and 46 m wide. Three additional bodies are much smaller. The outcrop patterns are linear, suggesting fracture or fault control. Porous zones of ellipsoidal cavities (vugs) with interstitial coarse-grained K-feldspar and quartz (less than 5 cm wide) are found within the episyenite and could represent fluid pathways, but it is uncertain if the open spaces are a result of dissolution or nondeposition of crystals. These zones locally grade into a breccia of cemented K-feldspar crystals. Within the lenses of episyenite, original amphibolite has been altered to a dark red-brown and greenish-black episyenite. The contacts between the brick-red episyenite and orange to buff-colored Caballo granite and black amphibolite are generally sharp. Two prospect pits have exposed the episyenites (Appendix 1), but only thin veins of manganese oxides, hematite, and clay are found cutting the episyenite. The episyenite lenses are unconformably overlain by the black to dark brown iron-rich sandstone of the Bliss Formation or are faulted adjacent to the Bliss ironstone or limestone. The overlying Bliss conglomerate locally contains pebbles and smaller fragments of episyenites, mixed with unaltered quartz and K-feldspar and pink granite pebbles and smaller fragments (Appendix 2).

Southern Red Hills

More than 25 lenticular to elongate pods, lenses (<100 m long, <10 m wide), narrow pipe-like and dike-like bodies (<2 m wide, 400 m long) of episyenites are found scattered throughout the Southern Red Hills, south of Apache Gap (Appendix 1) and locally form clusters or linear zones, possibly along local fracture or shear zones (Fig. 4). Episyenites are commonly exposed near pegmatite and aplite dikes. Several pits, one quarry, and one adit have exposed many of the episyenites (Appendix 1). Contacts between episyenites and the Caballo granite vary between sharp, irregular, and gradational. Within the episyenites, gradational contacts are characterized by an increase in grain size towards the contact. The episyenites typically consist of microcline (as determined by XRD), with subordinate amounts of quartz, muscovite, hematite/goethite, chlorite, and locally trace plagioclase and other accessory minerals. Some episyenites in the Southern Red Hills contain as much as 95% microcline, whereas other episyenites contain as much as 25% quartz. Some episyenites contain porous zones of ellipsoidal cavities (vugs) with interstitial coarse-grained K-feldspar and quartz (less than 5 cm wide) that could represent fluid pathways, similar to those found at Apache Gap. Many episyenites in the Southern Red Hills contain dark brown-green to brown to black aggregates (as much as 2 cm in diameter) of specular hematite and chlorite (as determined by XRD), with a variety of accessory minerals (Table 2).

MINERALOGY AND PARAGENESIS

Episyenite samples were examined by petrographic microscope and electron microscope to determine textures and mineralogy. Feldspars are subhedral to anhedral, and plagioclase (~25%) and K-feldspar (~35%) are both present. New growth of feldspar is observed as overgrowth rims and as replacements of pre-existing feldspar in the pre-existing granite from grain boundaries inward. Secondary feldspar is similar to feldspar in fully altered episyenite; i.e. K-rich, lacking exsolution textures, hematite-rich and turbid with fragmentary to subhedral grain boundaries. Most episyenites contain abundant fractured and vuggy K-feldspar with micron sized iron-oxide inclusions. Chlorite and vermiculite forms pseudomorphs after biotite, while the original diamond-shaped form of amphibole is replaced by fine-grained aggregates of chlorite, Fe-oxides, rutile, and possibly calcite. Apatite is euhedral and prismatic, while zircon is usually subhedral, rounded, and displays growth zoning. Calcite is present as late-stage fracture fill and is fine grained and turbid. Oxides are principally hematite, but magnetite and secondary rutile are present as well. Several samples also contain patchy cores of plagioclase and K-feldspar without iron-oxide inclusions surrounded by rims of K-feldspar with iron-oxide inclusions. Iron and titanium oxides are most commonly present in areas of apparent alteration of mafic xenoliths or aggregates of mafic minerals within the original granite. Some relict shapes and textures of primary mafic silicates are preserved. Vugs and fracture fillings contain quartz, and varying amounts of chlorite, apatite, iron and titanium oxides, zircon, calcite, fluorite, magnetite, barite, and U-, Th- and REE-bearing minerals (Table 2). At least three stages of fluorite (dark purple in color) are present in episyenites: an early disseminated fluorite adjacent to K-feldspars, fluorite along thin veinlets cutting K-feldspar, and late-stage fluorite in vugs and along fractures surfaces (Fig. 5). REE-bearing phases are typically associated with areas of altered mafic silicates and include synchysite, thorite, xenotime and uranophane (Fig. 5; Table 2). A few yellowish-brown minerals are also present that are likely monazite. Thorite locally occurs in ring structures and is commonly surrounded by iron-oxide. Episyenite sample REE-148 contains similar sized crystals of synchysite and thorite in contact with one another. The contacts are sharp and display no evident cross-cutting relationships. Synchysite is a major host of light REEs in the episyenites (63 wt.% light REE), while heavy REEs are concentrated predominantly in xenotime (16 wt.% heavy REE) and priorite (9 wt.%). Oxidation of uraninite to kasolite and uranophane is found at the Plainview adit. Uranophane commonly displays a scaly texture, suggesting dehydration. From

TABLE 2. Rare minerals found in the episyenites in the southern Caballo Mountains.

Mineral	Formula	Method of analysis	Comment
Apatite	$Ca_5(PO_4)_3(F,Cl,OH)$	Thin section, electron microprobe	
Zircon	$ZrSiO_4$	Thin section, electron microprobe	
Monazite	$(Ce,La)PO_4$	Thin section, electron microprobe	
Rutile	TiO_2	electron microprobe	
Synchysite	$Ca(Ce,La)(CO_3)2F$	electron microprobe	
Thorite	$(Th,U)SiO_4$	XRD, electron microprobe	
Thorogummite	$Th(SiO_4)_{0.9}(OH)_{0.4}$	XRD	
Xenotime	YPO_4	electron microprobe	
Uraninite	UO_2	XRD	
Uranophane	$Ca(UO_2)2SiO_3(OH)_2 \bullet 5(H_2O)$	electron microprobe, XRD	
Aeschynite	$(Y,Ca,Fe,Th)(Ti,Nb)_2(O,OH)_6$	electron microprobe	Longbottom Canyon
Priorite	$(Y,Ln,Ca,Th)(Ti,Nb)_2(O,OH)_6$		
Kasolite	$Pb(UO_2)SiO_4 \bullet H_2O$	XRD	Oxidation product of uraninite
Bastnaesite	$Ce(CO_3)F$	XRD	
Symplesite?	$Fe^{2+}_3(AsO_4)_2 \bullet 8H_2O$	XRD	
Uranopilite?	$(UO_2)_6(SO_4)O_2(OH)_6 \bullet 14H_2O$	XRD	
Fluorite	CaF_2	Visible, XRD	
Crandallite	$CaAl_3(PO_4)(PO_3OH)(OH)_6$	electron microprobe	
Pyrochlore	$(Na,Ca)_2Nb_2O_6(OH,F)$	electron microprobe	
Nb-rutile?	TiO_2	electron microprobe	

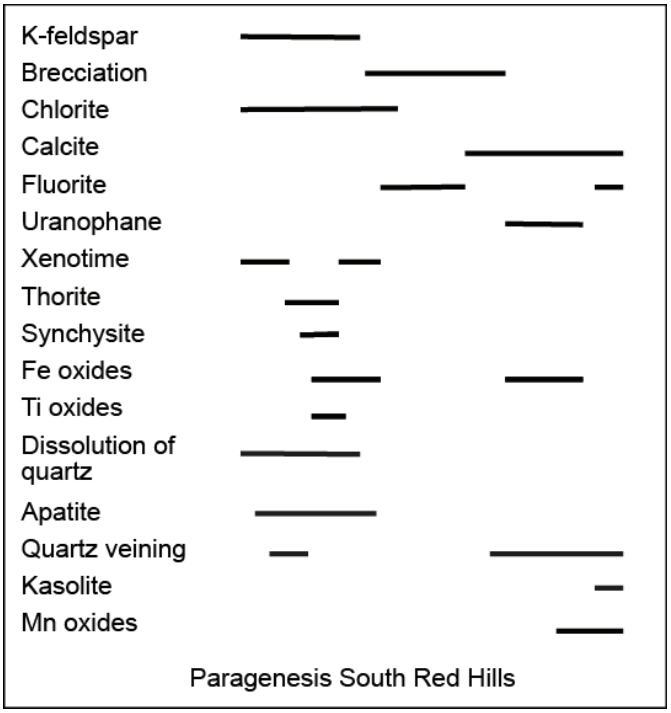

FIGURE 5. Paragenesis of U-Th-REE mineralization in the Southern Red Hills, Caballo Mountains.

these observations a paragenesis of the mineral assemblage was developed (Fig. 5). Table 2 summarizes the rare minerals found in the southern Caballo Mountains.

WHOLE-ROCK GEOCHEMISTRY

Selected samples of granite and episyenites in the Caballo Mountains were collected and analyzed for major and trace elements (Appendix 3). The Caballo episyenites are higher in K_2O (as high as 15.33%), Al_2O_3, Rb and slightly in Ba and lower in SiO_2, Sr and Na_2O (<0.4%) than samples of the Caballo granites (Riggins, 2012; Smith, 2018). Some episyenites have similar chondrite-normalized REE patterns (Fig. 6) as the Caballo granites, although other episyenite samples are enriched in REE (<2329 ppm), U (<9721 ppm), Th, (<1378 ppm), Nb (<247 ppm) and heavy REE (<133 ppm Yb and <179 ppm Dy) (Appendix 2). The Caballo episyenites are similar in composition to episyenites found in the Burro and Zuni Mountains, Sevilleta National Wildlife Refuge, and at Lobo Hill (McLemore, 1986, 2016; McLemore and McKee, 1988, 1989; McLemore et al., 1999; McMillan and McLemore, 2004; Riggins, 2014; Riggins et al., 2014).

DISCUSSION

Age of the episyenites

Detailed mapping has shown that episyenites in the Southern Red Hills of the Caballo Mountains are uncomformably overlain by the Cambrian–Ordovician Bliss Formation and thus record alteration of Precambrian rocks prior to about ~500 Ma. The basal transgressive conglomerate of the Bliss locally contains clasts of episyenites and granitic clasts adjacent to episyenite clasts in the basal Bliss are not altered (Appendix 2). Riggins (2014) analyzed a sample of the conglomerate on the electron microprobe, and found that the red episyenites grains have sharp, rounded boundaries. This indicates that the clasts are detrital, and were not formed in situ by an alteration or magmatic event. Additionally, several of the episyenites clasts contain xenotime with a similar REE pattern to xenotime from in-place episyenites bodies. This further indicates that episyenites were present in some form prior to the deposition of the Bliss Formation.

However, secondary K-feldspar from the Caballo episyenites yields $^{40}Ar/^{39}Ar$ ages mostly between ~309 to 437 Ma (Fig. 7; Riggins, 2014; Smith, 2018), which suggests potential crystallization during the Ancestral Rocky Mountain orogeny, and thus too young to directly record the pre-500 Ma metasomatic event. However in the Palomas Gap and Apache Gap areas, much younger ages were recorded from 34–55 Ma and 40–50 Ma, respectively. These were interpreted to record possible thermal resetting during the Laramide orogeny (Riggins, 2014; Smith, 2018). Nearby, unaltered primary K-feldspars from Proterozoic host rocks have $^{40}Ar/^{39}Ar$ age spectra that rise abruptly from initial ages between 550 and 700 Ma ages to near plateau ages ranging from ~925 to ~1050 Ma, indicating that the late Paleozoic ages of the secondary episyenite K-feldspar are not cooling ages, but rather represent K-feldspar recrystallization associated with low temperature alteration events (Table 1). The presence of numerous types of mineral deposits found in the Caballo Mountains, as described above, suggest that mineralizing fluids could have affected these rocks during the Paleozoic and are supportive of the variance in $^{40}Ar/^{39}Ar$ ages.

Formation of episyenites

Textures, high K-feldspar contents, and high K_2O concentrations support a metasomatic origin of the Caballo episyenites (McLemore, 1986; Riggins, 2014; Smith, 2018). The field and mineralogical observations suggest that the Caballo episyenites were formed by interaction of a K-rich fluid with the granitic host rock, possibly along fault, fracture, and shear zones. The most altered rocks contain more than 15 wt.% K_2O, which is close to the composition of endmember orthoclase (15.60 wt.% K_2O; Deer et al., 1992; Riggins, 2014; Riggins et al., 2014; Smith, 2018), suggesting the most altered rocks are composed almost completely of K-feldspar. The K-rich fluid that caused metasomatism was likely silica undersaturated, resulting in dissolution and/or alteration of primary quartz, biotite and other accessory silicate phases (Cathelineau, 1986), and precipitation of secondary K-feldspar with iron-oxide inclusions. Similar observations are found in the episyenites found in the Sevilleta Wildlife Refuge and Burro Mountains (Riggins, 2014; Riggins et al., 2014; McLemore, 2016).

One sample of the episyenite in the Burro Mountains yielded $^{40}Ar/^{39}Ar$ plateau ages of 516.4±4.5 to 533.3±5.2 Ma, which is consistent with formation during the Cambrian–Ordovician (Riggins, 2014). However, other samples from the Caballo and Burro Mountains yields complex and intriguing age results that

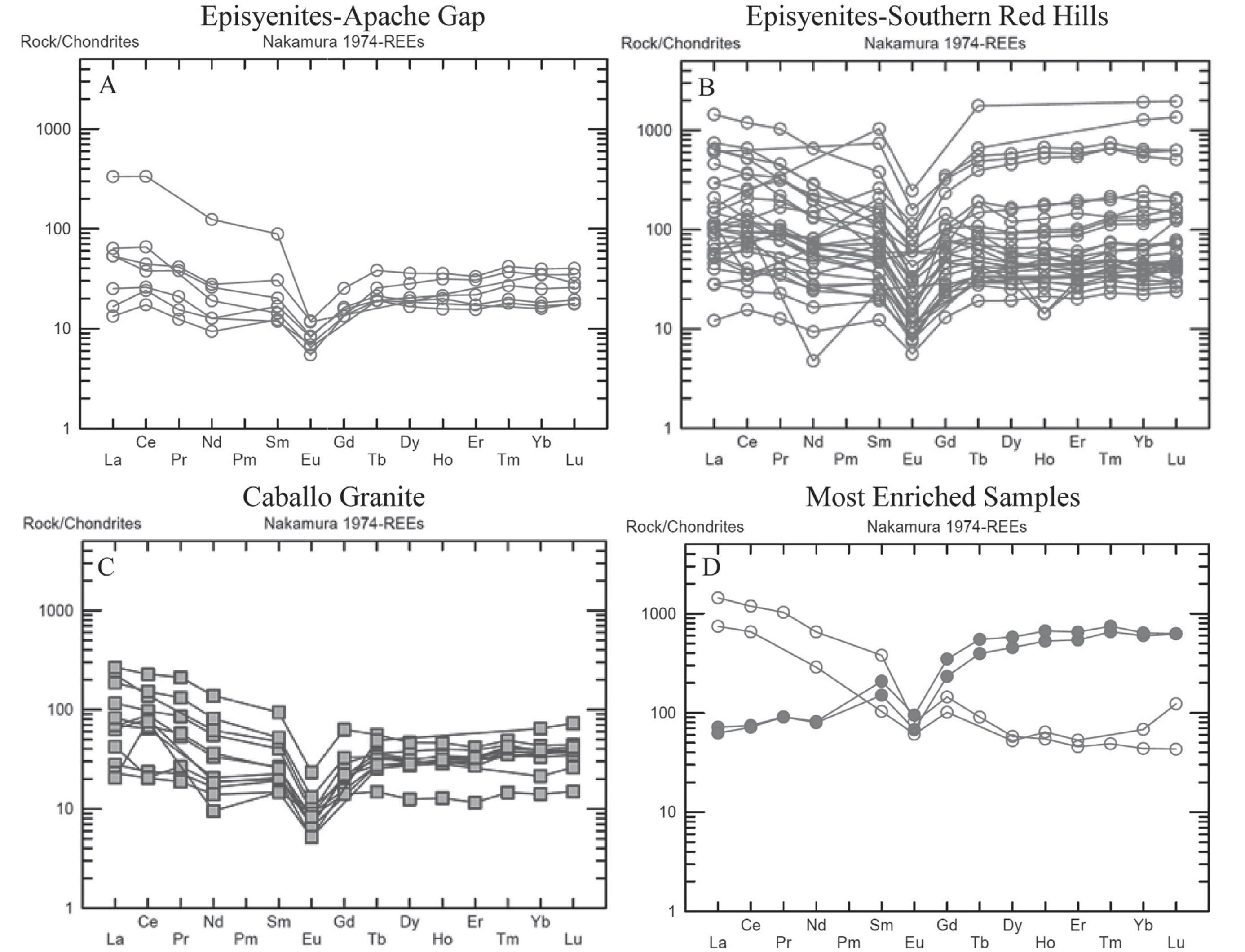

FIGURE 6. Chondrite normalized REE patterns for the Caballo granite and episyenites. Chondrite values from Nakamura (1974). Chemical analyses are in Appendix 3. 6D displays data from the most LREE enriched samples (hollow circles), and most HREE enriched samples (solid circles).

are likely related to multiple alteration events, and therefore cannot constrain the maximum age of episyenite formation (Riggins, 2014; Smith, 2018). $^{40}Ar/^{39}Ar$ ages suggests potential crystallization of new K-feldspar during the Ancestral Rocky Mountain orogeny and additional potential reheating during the Laramide orogeny. Collectively, these data clearly indicate that the Caballo episyenites were formed before ~500 Ma prior to Cambrian–Ordovician Bliss Formation, and subsequently reheated during alteration during the Ancestral Rocky Mountain and Laramide orogenies. Additional age dating is required to constrain the maximum age of episyenites, perhaps with in situ U-Pb dating of the xenotime, uraninite or thorite.

MINERAL-RESOURCE POTENTIAL

In general, the exposed outcrops of episyenites in the Caballo Mountains appear too small and low grade to be economic in today's market. There are no carbonatites exposed at the surface in the Caballo Mountains. However, drilling and subsurface sampling are required to fully evaluate the mineral-resource potential. The Lobo Hill episyenites near Moriarty are currently being mined for crushed decorative stone, and the Lobo Hill episyenites are approximately 20 m deep and drilling suggests episyenites extends another 20–30 m. Thus episyenites can be extensive in the subsurface. The relatively high HREE in some episyenites in the Caballo Mountains could be of economic interest, but additional mineralogical, geochemical, and economic analyses are required to fully assess the mineral-resource potential.

CONCLUSIONS

The episyenites in the southern Caballo Mountains are metasomatic in origin and the maximum age of the metasomatism forming the episyenites is between the age of the host granite (~1400 Ma) and the Cambrian–Ordovician Bliss Formation (~500 Ma). Subsequent metasomatism and recrystallization of K-feldspars occurred during the Ancestral Rocky Mountain and Laramide orogenies. Rare U, Th, Nb and REE minerals are found in the Caballo episyenites and could indi-

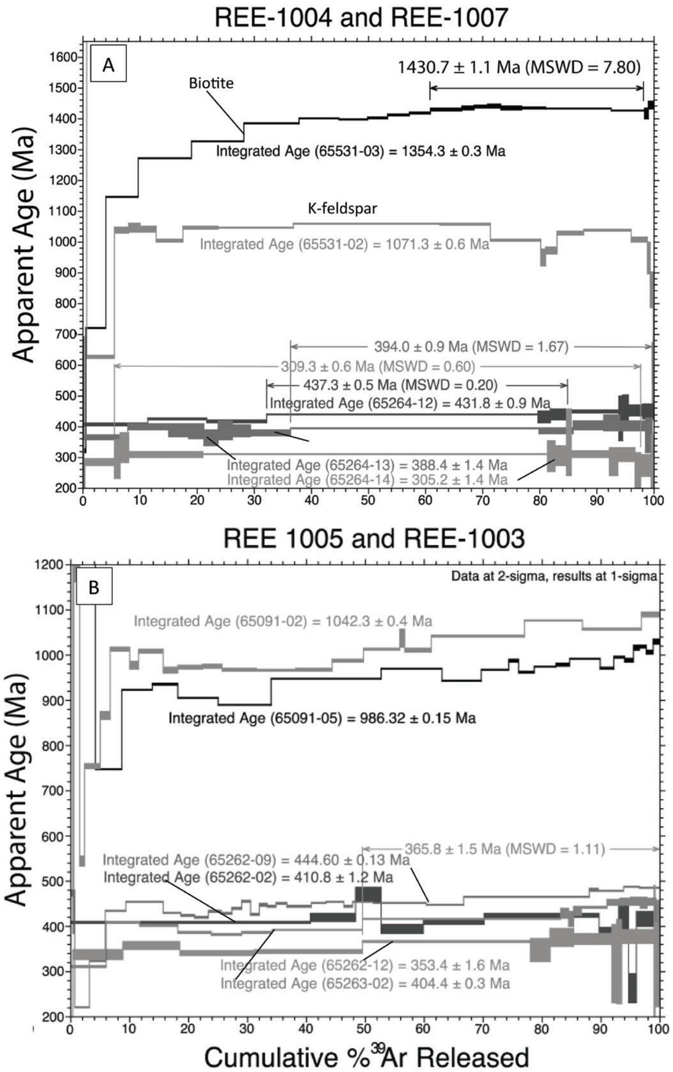

FIGURE 7. Age spectra from samples in the southern Red Hills of the Caballo Mountains. Integrated ages and are shown and for each spectrum and plateaus are identified when valid. **A**) Age spectra from REE-1004 (Caballo granite) and K-feldspar fragments from REE-1007 (fully altered episyenite). From REE-1004, both K-feldspar and biotite were dated. **B**) K-feldspar age spectra of coarse-grained Caballo granite (REE-1005) and the episyenite it hosts (REE-1003). In both cases, crystals from the granite define ages greater than ~800 Ma, while the episyenites define a range of ages from ~300–450 Ma.

cate potential REE mineralization at depth, including heavy REE, which are important economic commodities.

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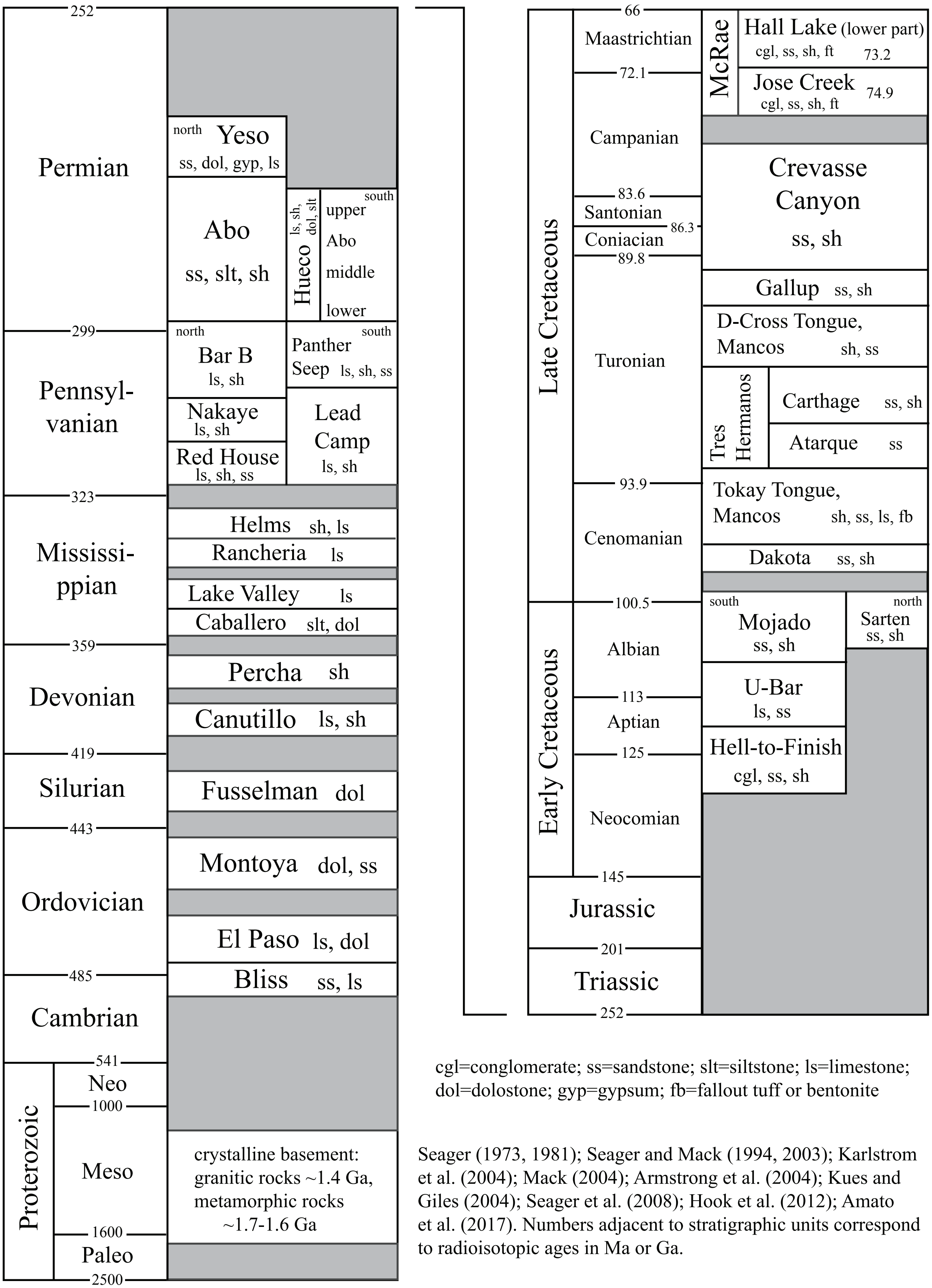
Supplemental data can be found at http://nmgs.nmt.edu/repository/index.cfml?rid=2018006

A view of the Organ Mountains. Photograph by Dana S. Ulmer-Scholle.



cgl=conglomerate; ss=sandstone; slt=siltstone; ls=limestone; dol=dolostone; gyp=gypsum; fb=fallout tuff or bentonite

Seager (1973, 1981); Seager and Mack (1994, 2003); Karlstrom et al. (2004); Mack (2004); Armstrong et al. (2004); Kues and Giles (2004); Seager et al. (2008); Hook et al. (2012); Amato et al. (2017). Numbers adjacent to stratigraphic units correspond to radioisotopic ages in Ma or Ga.