Episyenites in the Zuni Mountains, Cibola County, New Mexico — New interpretations

Virginia T. McLemore

2021, pp. 129-136. https://doi.org/10.56577/FFC-71.129

in:

Geology of the Mount Taylor area, Frey, Bonnie A.; Kelley, Shari A.; Zeigler, Kate E.; McLemore, Virginia T.; Goff, Fraser; Ulmer-Scholle, Dana S., New Mexico Geological Society 71st Annual Fall Field Conference Guidebook, 310 p. https://doi.org/10.56577/FFC-71

This page is intentionally left blank to maintain order of facing pages.

New Mexico Geological Society Guidebook, 71st Field Conference, Geology of the Mount Taylor Area, 2021, p. 129-135.

EPISYENITES IN THE ZUNI MOUNTAINS, CIBOLA COUNTY, NEW MEXICO — NEW INTERPRETATIONS

Virginia T. McLemore

New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro, NM, 87801; virginia.mclemore@nmt.edu

Abstract—Brick-red, K-feldspar-rich episyenites (altered rocks that were desilicated and metasomatized by alkali-rich solutions) are found in Proterozoic-age rocks in the Zuni Mountains in central New Mexico. The Zuni episyenites are high in K_2O and depleted in SiO_2 and Na_2O, with slightly enriched heavy REE patterns. The Zuni episyenites are similar in composition to episyenites found in the Caballo and Burro mountains, the Sevilleta National Wildlife Refuge, and at Lobo Hill, but the Zuni episyenites are lower in REE. The Zuni episyenites are younger than ~1000 Ma. Similar episyenites are found elsewhere in New Mexico and southern Colorado and are thought to be part of a Cambrian-Ordovician magmatic event that is documented throughout this region. Unlike episyenites in the Caballo and Burro mountains, which contain moderate to high concentrations of rare earth elements (REE), uranium, and thorium, the episyenites in the Zuni Mountains have little or no economic potential.

INTRODUCTION

Rare earth elements (REE) are considered critical minerals and are becoming more important in our technological society, especially in many of our electronic devices. REE include the 15 lanthanide elements (atomic numbers 57-71), yttrium (Y, atomic number 39), and scandium (Sc, atomic number 21), and are commonly divided into two chemical groups, the light REE (La through Eu) and the heavy REE (Gd through Lu, plus Sc and Y). REE are lithophile elements (or elements enriched in the crust) that have similar physical and chemical properties, and, therefore, occur together in nature. REE deposits have been reported from New Mexico (McLemore et al., 1988a, 1988b; Long et al., 2010; McLemore, 2015, 2018), but were not considered important exploration targets until recently, because the demand in past years has been met by other deposits in the world. However, with the projected increase in demand and potential lack of available production from Chinese deposits, areas in New Mexico are being re-examined for their REE potential (McLemore, 2015, 2018). One type of deposit in New Mexico containing REE is episyenite (Fig. 1; or metasomatite according to the International Atomic Energy Agency, 2018). The purpose of this paper is to update previous work (McLemore and McKee, 1989; McLemore, 2013) by describing the episyenite deposits in the Zuni Mountains, New Mexico, including presenting new geochemical analyses and evaluating their economic potential.

The Zuni Mountains are west and southwest of Grants in Cibola County, New Mexico (Fig. 1). Before 1983, the Zuni Mountains were in Valencia County; Cibola County was created from the western portion of Valencia County in 1983. The major types of mineral deposits in the Zuni Mountains include 1) veins and replacements in Proterozoic rocks, 2) stratabound, sedimentary-copper deposits, 3) fluorite veins, 4) episyenites REE-Th-U metasomatic bodies, 5) high-calcium limestone,

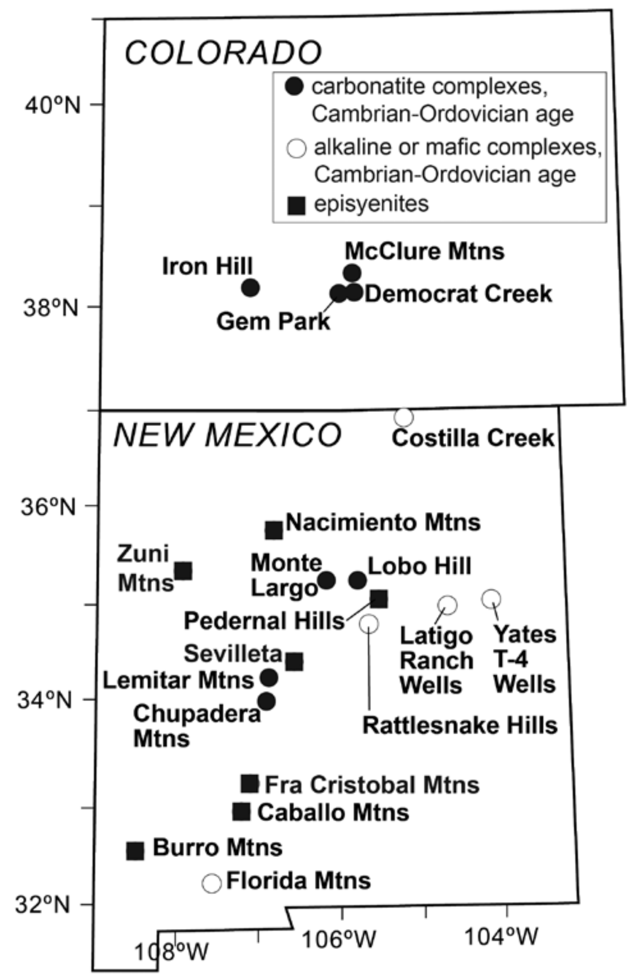

FIGURE 1. Cambrian-Ordovician carbonatites, alkaline and mafic intrusive igneous rocks, and episyenites in New Mexico and Colorado.

6) volcanic cinders (scoria), and 7) iron deposits (McLemore, 2001, 2013). Base and precious metals were found in the Zuni Mountains mining district circa 1900 and at least one metal mill was built in the district.

Episyenites have been known in the Zuni Mountains since the 1980s, but these rocks were generally called igneous syenites (Lambert, 1983; McLemore and McKee, 1989). McLemore and McKee (1989) briefly described and mapped the known occurrences of brick red, K-feldspar-rich, slightly radioactive (2-4 times background) deposits in the Zuni Mountains. Because some of these unusual rocks are known for potential economic deposits of REE, uranium (U), thorium (Th), niobium (Nb), zirconium (Zr), hafnium (Hf), gallium (Ga), and other elements (Long et al., 2010; McLemore, 2015; McLemore et al., 2018), the author remapped and sampled these episyenites to evaluate their mineral-resource potential, and to compare with new results of chemical analyses from episyenites elsewhere in New Mexico. Additional goals were to better understand their tectonic setting and origin. Similar episyenites found elsewhere in New Mexico and southern Colorado are thought to be part of a Cambrian-Ordovician magmatic event that is documented in this region (Fig. 1; McMillan and McLemore, 2004; Riggins et al., 2014). This Cambrian-Ordovician magmatic event is characterized by the intrusion of carbonatites, syenites, monzonites, alkaline granites, and mafic dikes, and is associated with K-metasomatism (i.e. fenites and episyenites) and REE-Th-U mineral deposition.

DEFINITION OF EPISYENITES

The term *episyenite* is used to describe altered rocks that were desilicified and metasomatized by alkali-rich fluids (Leroy, 1978; Recio et al., 1997; Suikkanen and Rämö, 2019). These deposits are also known for their elevated uranium content and are called metasomatite deposits by the International Atomic Energy Agency (2018). Brick-red outcrops in several areas in New Mexico, including the Caballo, Burro, and Zuni mountains and Lobo Hill, were erroneously identified as magmatic syenites and alkali granites (McMillan and McLemore, 2004), but these rocks are actually metasomatic rocks (McLemore, 2013; Riggins, 2014; Riggins et al., 2014). Elsewhere in the world, alkali-rich metasomatic rocks are associated with U and Th deposits (Costi et al., 2002; Condomines et al., 2007; Cuney et al., 2012; International Atomic Energy Agency, 2018; Suikkanen and Rämö, 2019), gold deposits (López-Moro et al., 2013) and tin-tungsten deposits (Charoy and Pollard, 1989; Costi et al., 2002; Borges et al., 2009), but unmineralized episyenites are found as well (Petersson and Eliasson, 1997; Recio et al., 1997; Hecht et al., 1999; Suikkanen and Rämö, 2019). 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 (LeBas, 2008). However, we are reluctant to use the term fenite for the rocks studied here because there is no definitive spatial and temporal association with carbonatite or alkaline igneous rocks in the vicinity of the episyenites.

PREVIOUS WORK

This work is part of ongoing studies of mineral deposits in New Mexico conducted by the NMBGMR. The Zuni Mountains were mapped by Goddard (1966) and Lambert (1983). Investigations of the mineral deposits and plutonic rocks in the Zuni Mountains by this author began in 1983 in order to assess their U potential (McLemore, 1983, 1989; McLemore and McKee, 1989). Continued investigations occurred in 1985-1986, as part of the evaluation of mineral resources of Cibola County (McLemore et al., 1986). During 2011-2012, investigations continued in the area in order to evaluate the REE mineral-resource potential (McLemore, 2013). The episyenites were examined in more detail during 2013 and 2018-2019. This report presents new chemical analyses and interpretations that differ from, and update, earlier preliminary reports by McLemore and McKee (1989) and McLemore (2013).

METHODOLOGY

A detailed geologic map was compiled in ArcMap using USGS topographic maps as the map base and by detailed field mapping at a scale of approximately 1:6000 (Fig. 2). A handheld GPS unit was used with the current topography loaded in the unit to more accurately map the episyenites. Locations of samples, whole-rock geochemical analyses, QA/QC (quality assurance and quality control), specific methods of analysis for each element, and detection limits are in Appendix 1.

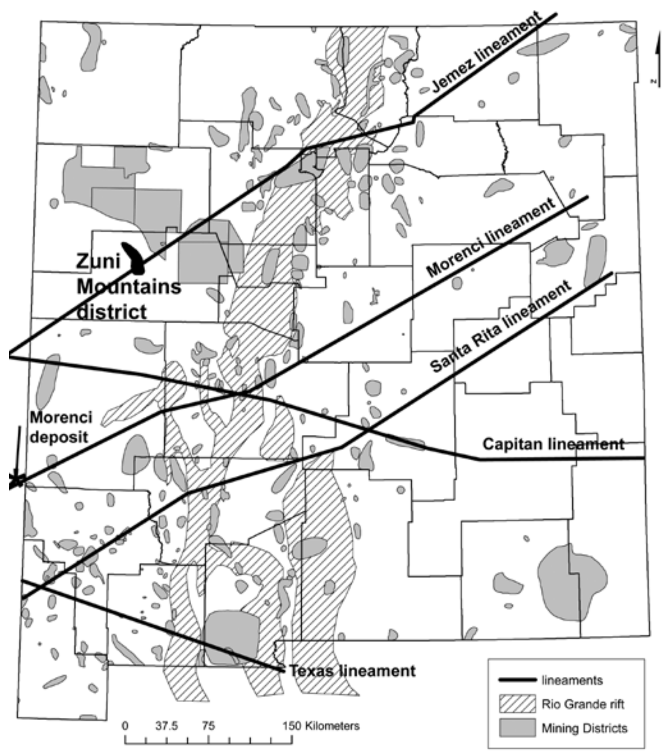

FIGURE 2. Lineaments and mining districts in New Mexico (from McLemore, 2013 as modified from Chapin et al., 1978, 2004; McLemore, 2001; Sims et al., 2002). The Zuni Mountains lie along the Jemez Lineament.

Selected samples of the Proterozoic host rocks and episyenites were collected and analyzed by X-ray fluorescence (XRF) spectroscopy and inductively coupled plasma spectroscopy (ICP-OES and ICP-MS) by Activation Laboratories in 2012 and 2015, methods for which can be found at https://cdn.actlabs.com/wp-content/uploads/2019/10/Actlabs-Schedule-of-Services-Canada-2019-07-22.pd and https://actlabs.com/geochemistry/lithogeochemistry-and-whole-rock-analysis/ and summarized here. The entire sample is crushed to <2 mm, mechanically split to obtain a representative sample and then pulverized to at least 95% <105 microns (μm). All of the steel mills are mild steel and do not introduce Cr or Ni contamination. The method of sample analysis is by lithochemistry research analyses, which employs the most aggressive fusion technique (a lithium metaborate/tetraborate fusion). Fusion is performed by a robot at Actlabs, which provides a fast fusion of the highest quality in the industry. The resulting molten bead is rapidly digested in a weak nitric acid solution. The fusion ensures that the entire sample is dissolved. Then the sample is analyzed by XRF for major elements and ICP-MS for trace elements. Uncertainty of analyses is generally <5%, and duplicate samples and standards were analyzed (Appendix 1).

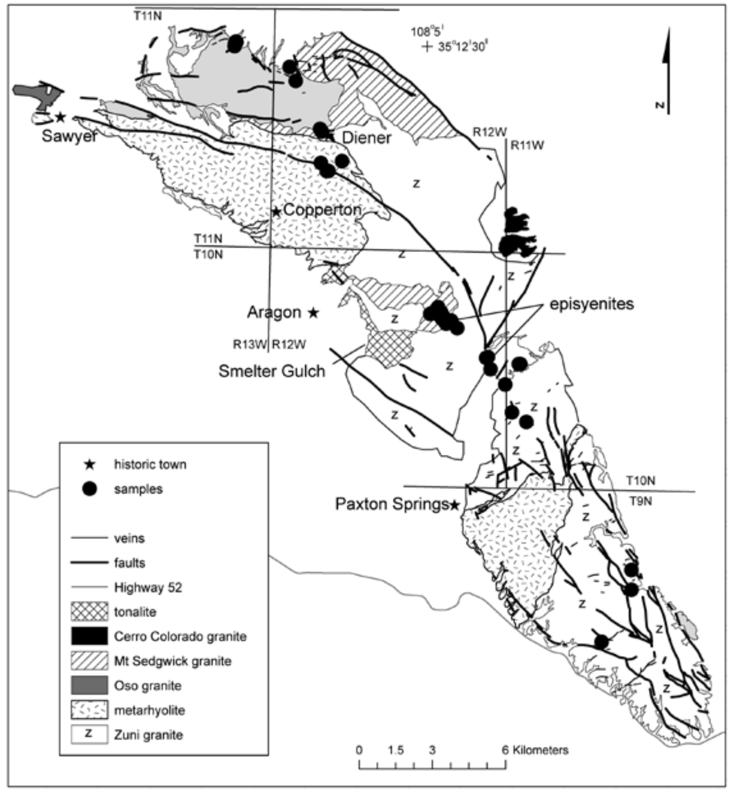

FIGURE 3. Simplified geologic map of the Zuni Mountains (modified by the author from field reconnaissance; from Goddard, 1966 and McLemore, 2013) showing sample locations (McLemore, 2013; Appendix 1). Zuni granite includes metamorphic rocks and aplite.

GEOLOGIC SETTING

The Zuni Mountains lie along the Jemez Lineament, which is defined by northeast-trending alignment of late Cenozoic volcanic fields that extend from the San Carlos field in Arizona to the Raton-Clayton field in northeastern New Mexico and Colorado (Fig. 2; Chapin et al., 1978; Aldrich et al., 1986; Goff and Kelley, this volume). A mafic intrusion of late Cenozoic age likely underlies the Zuni uplift as indicated by geophysical data (Ander and Huestis, 1982) and the presence of a Quaternary basaltic vent in the core of the range (Maxwell, 1986). Proterozoic granite and metamorphic rocks form the core of the Zuni Mountains (Fig. 3) and are unconformably overlain by sedimentary deposits of Permian age (Abo, Yeso and San Andres formations; Goddard, 1966). Episyenites are found only in Proterozoic rocks. The youngest volcanic formations in the area are Quaternary basalt flows and scoria cones of the Zuni-Bandera volcanic field.

DESCRIPTION OF PROTEROZOIC ROCKS AND EPISYENITES IN THE ZUNI MOUNTAINS

Proterozoic granite and metamorphic rocks

The oldest rocks in the area are hornblendite and serpentinized peridotite (1630.2±2 Ma, $^{40}Ar/^{39}Ar$, Strickland et al., 2003), and a metarhyolite with an U/Pb age of about 1655 Ma (Bowring and Condie, 1982). Other rock types in the Zuni Mountains Proterozoic terrain include gneiss, schist, amphibolite, syenite, pegmatites, and diabase dikes (Goddard, 1966; Fitzsimmons, 1967; Lambert, 1983; Mawer and Bauer, 1989; Strickland et al., 2003). The diabase dikes are 1130±20 Ma ($^{40}Ar/^{39}Ar$, Strickland et al., 2003).

Existing data suggest four geographically and geochemically distinct granites are present in the Zuni Mountains (Fig. 2; Condie, 1978; McLemore, 2013): Mt. Sedgwick granite (high calcium), Zuni granite (high silica), Cerro Colorado gneissic aplite (high silica), and Oso granite (high potassium). A fifth unnamed pluton in the northern Zuni Mountains has not been sampled. The megacrystic granite, the Mt. Sedgwick granite, has a $^{40}Ar/^{39}Ar$ age of 1432±2 Ma (Strickland et al., 2003). The metarhyolite is similar geochemically to the Oso granite and the Zuni and Cerro Colorado granites are geochemically similar to each other. The Zuni Mountain granites are calcic to calc-alkaline and peraluminous granites. Condie (1978) suggested that the high-calcium granites were formed by partial melting of siliceous granulite in the lower crust and the high-silica and high-potassium granites formed by fractional crystallization of shallow high-calcium magmas.

Episyenites

Several radioactive, pink to red, small stock-like to flat-lying tabular bodies (<300 m long), near-vertical pipes (<30 m in diameter), and dike-like bodies (<2 m wide, 400 m long) of episyenites are mapped (Fig. 3). Outcrops are prominent (Fig. 4) and the contacts between the episyenite bodies and the host rocks vary from location to location, from very sharp to distinctly gradational crosscutting the foliation of the host rock.

Zones of vuggy breccia are found in some of the episyenites (Fig. 5), suggesting fluid migration. The episyenites vary in texture from fine-grained to coarse-grained, and are similar in texture to the host granite or metarhyolite.

The episyenites contain 20-80% alkali-feldspar, 20-40% plagioclase, 0-10% quartz, 1-5% opaque minerals (predominantly iron oxides), trace-5% biotite (partially to completely altered to chlorite), and trace amounts of apatite, sericite, and calcite. Some alkali-feldspar crystals are more than a centimeter long. Plagioclase is commonly altered to carbonate, hematite, and clay. Iron oxides occur as fine-grained red-brown disseminations within the feldspars, and as small red cubes and octahedrons that were probably once magnetite. The rocks are almost devoid of ferromagnesian minerals. Chlorite, commonly vermicular, fills cavities and fractures, and replaces primary magmatic phases.

FIGURE 5. Episyenite with zones of vuggy breccia.

WHOLE-ROCK GEOCHEMISTRY

Selected samples of granite and episyenites in the Zuni Mountains were analyzed for major and trace elements (Appendix 1). Most Zuni episyenites are high in K_2O (as high as 15.7%) and are depleted in SiO_2 and Na_2O (Fig. 6, 7), with slightly enriched heavy REE patterns (Fig. 8). Generally, the episyenites contain higher concentrations of K_2O, Al_2O_3, Rb, and Ba and lower concentrations of Na_2O and Sr than the granites and metarhyolites in the Zuni Mountains (Fig. 6; Appendix 1). The episyenites have similar chondrite-normalized REE patterns as the host granites and metarhyolites (Fig. 8; Appendix 1). Note that the concentrations of TiO_2, P_2O_5, and Y are similar in concentration to the granites (Appendix 1). The episyenites in the Zuni Mountains contain <16 ppm Th, <4 ppm U, <14 ppm Nb, <147 ppm Y, and <200 ppm total REE (Appendix 1), which are uneconomic concentrations. The Zuni episyenites are similar in composition to episyenites found in the Caballo and Burro Mountains, Sevilleta National Wildlife Refuge, and at Lobo Hill, but the Zuni episyenites are lower in REE (Fig. 8; McLemore, 1986, 2016; McLemore and McKee,

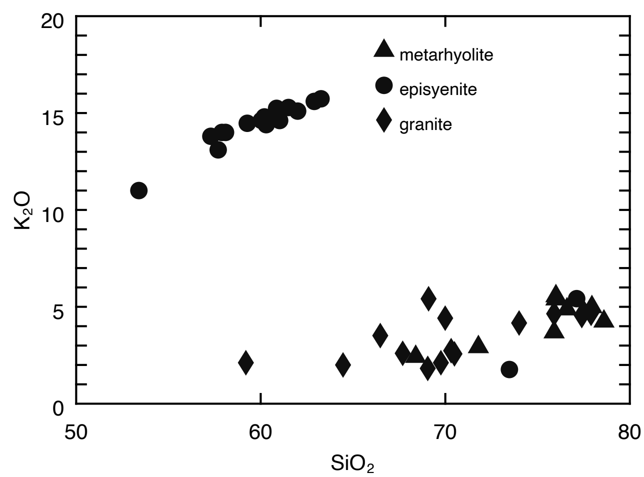

FIGURE 6. SiO_2 verses K_2O plot of the Zuni granites and episyenites. Chemical analyses are in Appendix 1 (including QA/QC). Uncertainty of analyses is generally <5% (Appendix 1).

FIGURE 4. Rugged outcrops of brick red episyenite (upper center).

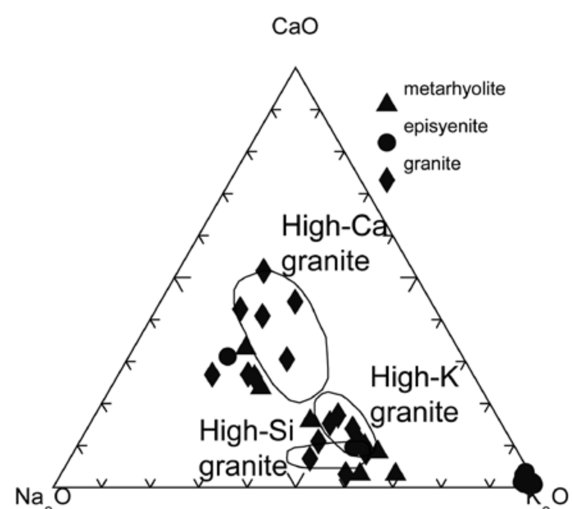

FIGURE 7. Na_2O-CaO-K_2O plot of the Zuni granites and episyenites. Geochemical fields shown after Condie (1978). Chemical analyses are in Appendix 1 (including QA/QC). Uncertainty of analyses is generally <5% (Appendix 1).

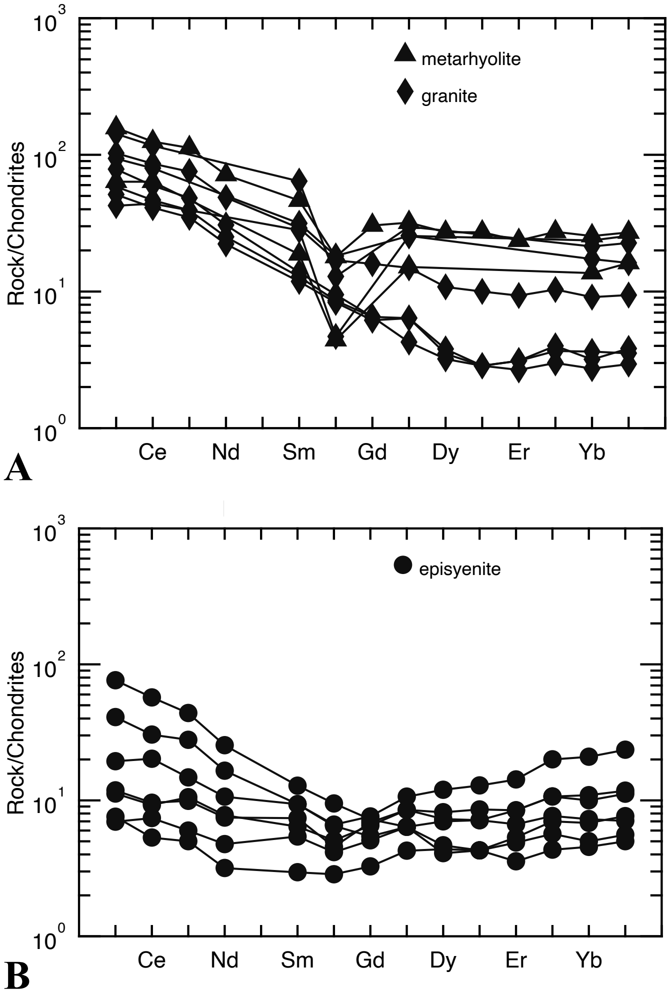

FIGURE 8. Similar sample/chondrite normalized REE patterns for the Zuni episyenites (**A**) and granites and metarhyolites (**B**). Chondrite values from Nakamura (1974). Chemical analyses are in Appendix 1 (including QA/QC). Uncertainty of analyses is generally <5% (Appendix 1).

1988, 1989; McLemore et al., 1999, 2018; McMillan and McLemore, 2004; Riggins, 2014; Riggins et al., 2014; Smith, 2018).

DISCUSSION AND CONCLUSIONS

Origin of episyenites

Replacement textures, high K-feldspar contents, and high K_2O concentrations support a metasomatic origin of the Zuni episyenites. The field and mineralogical observations suggest that the Zuni episyenites were formed by interaction of a K-rich fluid with granitic host rocks, possibly along faults, fractures, and shear zones. The most altered rocks contain more than 15 wt.% K_2O, which is close to the composition of end-member orthoclase (15.6 wt% K_2O; Deer et al., 1992; Riggins, 2014; Riggins et al., 2014), suggesting the most altered rocks are composed almost completely of newly formed secondary 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 characteristics are observed in the episyenites found in the Caballo and Burro mountains (Riggins, 2014; Riggins et al., 2014; Smith, 2018; McLemore et al., 2018).

Episyenite texture, mineralogy and mineral chemistry from the Caballo, Burro, and Zuni mountains suggest that processes that formed the episyenites was K-metasomatism, with the original fluids possibly derived from carbonatites or alkaline melts, then possibly altered again by younger fluids (Riggins, 2014; Riggins et al., 2014; Smith, 2018; McLemore et al., 2018). Carbonatites and alkaline intrusive rocks are commonly enriched in sodium, potassium and REE, due to magmatic processes such as crystal fractionation and late magmatic hydrothermal activity (Sheard et al., 2012; Gysi and Williams-Jones, 2013; Walters et al., 2013). Primitive carbonatitic melts contain significant amounts of sodium and potassium that are incompatible in the crystallizing assemblage, and are fractionated into the residual melt, which can then be lost to late-stage metasomatic fluids (LeBas, 2008). However, some researchers suggest that granitic intrusions could provide the heat necessary for meteoric fluid circulation resulting in the formation of episyenites (Leroy, 1978; Cuney et al., 2012; Petersson et al., 2014; Suikkanen and Rämö, 2019); whereas others suggest that hydrothermal fluids formed by regional thermal anomalies within post-orogenic crust during extension, provide the fluids and heat to form episyenites (Boulvais et al., 2007; Jaques et al., 2016; Smith, 2018). Additional study is needed to identify the source of the original fluids that formed episyenites.

Age of episyenites

The episyenites are metasomatized Proterozoic granite and metarhyolite. Strickland et al. (2003) dated an episyenite as <700 to 1000 Ma ($^{40}Ar/^{39}Ar$), but the age spectra is disturbed and does not provide an accurate age. Most episyenites dated ($^{40}Ar/^{39}Ar$) from the Caballo Mountains also exhibit disturbed spectra and do not provide accurate ages (Riggins, 2014; Smith, 2018). Fluids of varying ages are suspected to have reset the feldspar ages (Smith, 2018; McLemore et al., 2018; Suikkanen and Rämö, 2019). Fluids have migrated along the Jemez Lineament since Proterozoic times, as evidenced by varying ages of igneous intrusions and mineral deposits in the Zuni Mountains (Chapin et al., 1978, 2004; Aldrich et al., 1986; McLemore, 2013). Thus the age of the episyenites is still uncertain but is probably Proterozoic (700-1000 Ma) or Cambrian-Ordovician (~500 Ma). The metasomatic hydrothermal alteration is not related to late Cenozoic volcanism of the Zuni-Bandera volcanic field.

Outlook for mineral resource potential in the future

Unlike episyenites in the Caballo and Burro mountains, the episyenites in the Zuni Mountains have little to no economic potential, except perhaps as red decorative stone. Episyenites at Lobo Hill, near Moriarty have been mined for decorative stone and are at least 30 m thick. A few Zuni episyenites are radioactive, but all Zuni samples are low in U, Th, yttrium, niobium and REE (Appendix 1; Fig. 8). It is possible that the Zuni episyenites could be enriched in U, Th, yttrium, niobium and REE at depth, but drilling is required to investigate their subsurface potential. Future research could include mineral chemistry (identification of REE, uranium, and thorium minerals) and more precise dating of these rocks, especially in the Lobo Hill area where the episyenites have been exposed by quarrying.

ACKNOWLEDGMENTS

This paper and related studies are part of an on-going study of the mineral resources of New Mexico at NMBGMR, Dr. Nelia Dunbar, Director and State Geologist, and were partially funded by USGS Mineral Resources External Research Program (award number G12AP20051). Miles Silberman and Nelia Dunbar reviewed an earlier version of this manuscript and their comments are greatly appreciated. Additional reviews were provided by Shari Kelley (NMBGMR) and Fraser Goff (NM Tech).

REFERENCES

Aldrich, M.J., Laughlin, A.W., Meade, J.S., and Peirce, H.W., 1986, The Jemez lineament: structural boundaries and control on sedimentary facies, tectonism and mineralization: Proceedings of the 6th International Conference on Basement Tectonics, p. 104-113.

Ander, M.E. and Huestis, S.P., 1982, Mafic intrusion beneath the Zuni-Bandera volcanic field, New Mexico: Geological Society of America Bulletin, v. 93, p. 1142-1150.

Borges, R.M.K., Villas, R.N.N., Fuzikawa, K., Dall'Agnol, R., and Pimenta, M.A., 2009, Phase separation, fluid mixing, and origin of the greisens and potassic episyenite associated with the Água Boa pluton, Pitinga tin province, Amazonian craton, Brazil: Journal of South American Earth Science, v. 27, p. 161-183.

Boulvais, P., Ruffet, G., Cornichet, J., and Mermet, M., 2007, Cretaceous albitization and dequartzification of Hercynian peraluminous granite in the Salvezines Massif (French Pyrénées): Lithos, v. 93, p. 89-106.

Bowring, S.A. and Condie, K.C., 1982, U-Pb zircon ages from northern and central New Mexico: Geological Society of America, Abstracts with Programs, v. 14, p. 304.

Cathelineau, M., 1986, The hydrothermal alkali metasomatism effects on granitic rocks: quartz dissolution and related subsolidus changes: Journal of Petrology, v. 27, p. 945-965.

Chapin, C.E., Chamberlin, R.M., Osburn, G.R., White, D.W., and Sanford, A.R., 1978, Exploration framework of the Socorro geothermal area, New Mexico: New Mexico Geological Society, Special Publication 7, p. 115-129.

Chapin, C.E., McIntosh, W.C., and Chamberlin, R.M., 2004, The Late Eocene-Oligocene peak of Cenozoic volcanism in southwestern New Mexico, *in* Mack, G.H. and Giles, K.A., eds., The Geology of New Mexico, a geologic history: New Mexico Geological Society, Special Publication 11, p. 271-293.

Charoy, B. and Pollard, P.J., 1989, Albite-rich, silica-depleted metasomatic rocks at Emuford, northeast Queensland: mineralogical, geochemical, and fluid inclusion constraints on hydrothermal evolution and tin mineralization: Economic Geology, v. 84, p. 1850-1874.

Condie, K.C., 1978, Geochemistry of Proterozoic granitic plutons from New Mexico, U.S.A.: Chemical Geology, v. 21, p. 131-149.

Condomines, M., Loubeau, O., and Patrier, P., 2007, Recent mobilization of U-series radionuclides in the Bernardan U deposit (French massif central): Chemical Geology, v. 244, p. 304-315.

Costi, H.T., Dall'Agnol, R., Borges, R.M.K., Minuzzi, O.R.R., and Teixeira, J.T., 2002, Tin-bearing sodic episyenites associated with the Proterozoic, A-type Água Boa Granite, Pitinga mine, Amazonian craton, Brazil: Gondwana Research, v. 5, p.435-451.

Cuney, M., Emetz, A., Mercadier, J., Mykchaylov, V., Shunko, W., and Yuslenko, A., 2012, Uranium deposits associated with Na-metasomatism from central Ukraine: A review of some of the major deposits and genetic constraints: Ore Geology Reviews, v. 44, p. 82-106.

Deer, W.A., Howie, R.A., and Zussman, J., 1992, An Introduction to the Rock-forming Minerals: Hong Kong, Longman Scientific & Technical, v. 2, 696 p.

Fitzsimmons, J.P., 1967, Precambrian rocks of the Zuni Mountains: New Mexico Geological Society, Guidebook 18, p. 119-121.

Goddard, E. N., 1966, Geologic map and sections of the Zuni Mountains fluorspar district, Valencia County, New Mexico: U. S. Geological Survey, Miscellaneous Geologic Investigations Map I-454, scale 1:31,680.

Goff, F., and Kelley, S.A., 2020, Facts and hypotheses regarding the Miocene – Holocene Jemez Lineament, New Mexico, Arizona, and Colorado: New Mexico Geological Society, Guidebook 71, this volume.

Gysi, A.P., and Williams-Jones, A.E., 2013, Hydrothermal mobilization of pegmatite-hosted REE and Zr at Strange Lake, Canada: A reaction path model: Geochimica et Cosmochimica Acta, v. 122, p. 324-352.

Hecht, L., Thuro, K., Plinninger, R., and Cuney, M., 1999, Mineralogical and geochemical characteristics of hydrothermal alteration and episyenitization in the Königshain granites, northern Bohemian massif, Germany: International Journal of Earth Sciences, v. 88, p. 236-252.

International Atomic Energy Agency, 2018, Geological classification of uranium deposits and selected examples: IAEA-TECDOC-1842, 430 p., https://www-pub.iaea.org/MTCD/Publications/PDF/TE1842_web.pdf.

Jaques, L., Noronha, F., Liewig, N., and Bobos, I., 2016, Paleofluids circulation associated with the Gerês late-orogenic granitic massif, northern Portugal: Chem Erde Geochem, v. 76, p. 659-676.

Lambert, E.E., 1983, Geology and petrochemistry of ultramafic and orbicular rocks, Zuni Mountains, Cibola County, New Mexico [M.S. thesis]: Albuquerque, University New Mexico, 166 p.

LeBas, M.J., 2008, Fenites associated with carbonatites: Canadian Mineralogist, v. 46, p. 915-932.

Leroy, J., 1978, The Margnac and Fanay uranium deposits of the La Crouzille district (western Massif Central, France): Geologic and fluid inclusion studies: Economic Geology, v. 73, p. 1611-1634.

Long, K.R., van Gosen, B.S., Foley, N.K. and Cordier, D., 2010, The principle rare earth element deposits of the United States—A summary of domestic deposits and a global perspective: U.S. Geological Survey, Scientific Investigations Report 2010-5220, 104 p., http://pubs.usgs.gov/sir/2010/5220/.

López-Moro, F.J., Moro, M.C., Timón, S.M., Cembranos, M.L., and Cóar, J., 2013, Constraints regarding gold deposition in episyenites: the Permian episyenites associated with the Villacampo shear zone, central western Spain: International Journal of Earth Sciences (Geol Rundsch), v. 102, p. 721-744.

Mawer, C.K. and Bauer, P.W., 1989, Precambrian rocks of the Zuni uplift: A summary with new data on ductile shearing: New Mexico Geological Society, Guidebook 40, p. 13-147.

Maxwell, C.H., 1986, Geologic map of El Malpais lava field and surrounding areas, Cibola County, New Mexico: U.S. Geological Survey, IMAP 1595, scale 1:62,500.

McLemore, V.T., 1983, Carbonatites in the Lemitar and Chupadera Mountains, Socorro County, New Mexico: New Mexico Geological Society, Guidebook 34, p. 235-240.

McLemore, V.T., 1986, Geology, geochemistry, and mineralization of syenites in the Red Hills, southern Caballo Mountains, Sierra County, New Mexico: New Mexico Geological Society, Guidebook 37, p. 151-159.

McLemore, V.T., 1989, Base and precious metal deposits in the Zuni Mountains, Cibola County, New Mexico: New Mexico Geological Society, Guidebook 40, p. 317-319.

McLemore, V. T., 2001, Silver and gold resources in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Resource Map 21, 60 p.

McLemore, V.T., 2013, Geology and mineral resources in the Zuni Mountains mining district, Cibola County, New Mexico: Revisited: New Mexico Geological Society, Guidebook 64, p. 131-142.

McLemore, V.T., 2015, Rare Earth Elements (REE) Deposits in New Mexico: Update: New Mexico Geology, v. 37, p. 59-69, http://geoinfo.nmt.edu/publications/periodicals/nmg/current/home.cfml.

McLemore, V.T., 2016, Episyenites in the Sevilleta National Wildlife Refuge, Socorro County, New Mexico—preliminary results: New Mexico Geo-

logical Society, Guidebook 67, p. 255-262.
McLemore, V.T., 2018, Rare earth elements (REE) deposits associated with Great Plain margin deposits (alkaline-related), southwestern United States and eastern Mexico: *Resources,* v. *7*(1), 8; 44 p., doi:10.3390/resources7010008; http://www.mdpi.com/2079-9276/7/1/8.
McLemore, V.T., and McKee, C., 1988, Geochemistry of Burro Mountains syenites and adjacent Proterozoic granite and gneiss and the relationship of a Cambrian–Ordovician magmatic event in New Mexico and southern Colorado: New Mexico Geological Society, Guidebook 39, p. 89-98.
McLemore, V.T. and McKee, C, 1989, Geology and geochemistry of syenites and adjacent Proterozoic granitic and metamorphic rocks in the Zuni Mountains, Cibola County, New Mexico: New Mexico Geological Society, Guidebook 40, p. 149-155.
McLemore, V.T., Broadhead, R.F., Barker, J.M., Austin, G.S., Klein, K., Brown, K.B., Murray, D., Bowie, M.R., and Hingtgen, J.S., 1986, A preliminary mineral-resource potential of Cibola County, northwestern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report OF-230, 403 p.
McLemore, V.T., McMillan, N.J., Heizler, M., and McKee, C., 1999, Cambrian alkaline rocks at Lobo Hill, Torrance County, New Mexico: More evidence for a Cambrian-Ordovician aulacogen: New Mexico Geological Society, Guidebook 50, p. 247-253.
McLemore, V.T., North, R.M., and Leppert, S., 1988a, Rare-earth elements (REE), niobium and thorium districts and occurrences in New Mexico: New Mexico Bureau of Mines and Mineral Resources, OF-324, 28 p.
McLemore, V.T., North, R.M., and Leppert, S., 1988b, Rare-earth elements (REE) in New Mexico: New Mexico Geology, v. 10, p. 33-38.
McLemore, V.T., Smith, A., Riggins, A.M., Dunbar, N., Frempong, K.B., and Heizler, M.T., 2018, Characterization and origin of episyenites in the southern Caballo Mountains, Sierra County, New Mexico: New Mexico Geological Society, Guidebook 69, p. 207-216.
McMillan, N.J. and McLemore, V.T., 2004, Cambrian-Ordovician magmatism and extension in New Mexico and Colorado: New Mexico Bureau of Mines and Geology Resources, Bulletin 160, 12 p., http://geoinfo.nmt.edu/publications/bulletins/160/downloads/01mcmill.pdf (accessed 8/22/11).
Nakamura, N., 1974, Determination of REE, Ba, Fe, Mg, Na, and K in carbonaceous and ordinary chondrites: Geochimica et Cosmochimica Acta, v. 38, p. 757-775.
Petersson, J. and Eliasson, T., 1997, Mineral evolution and element mobility during episynitization (dequartzification) and albitization in the post-kinematic Bohus granite, southwest Sweden: Lithos, v. 42, p. 123-146.
Petersson, J., Fallick, A.E., Broman, C., Eliasson, T., 2014, Imprints of multiple fluid regimes on episyenites in the Bohus granite, Sweden. Lithos v. 196-197, p. 99-114.
Recio, C., Fallick, A.E., Ugidos, J.M., and Stephens, W.E., 1997, Characterization of multiple fluid-granite interaction processes in the episyneites of Avila-Béjar, central Iberian massif, Spain: Chemical Geology, v. 143, p. 127-144.
Riggins, A.M., 2014, Origin of the REE-bearing episyenites in the Caballo and Burro Mountains, New Mexico [M.S. thesis]: Socorro, New Mexico Institute of Mining and Technology, 348 p.
Riggins, A.M., Dunbar, N., McLemore, V.T., Heizler, M., McIntosh, W. and Frempong, K., 2014, Mineralogy, geochemistry, and chronology of the Caballo and Burro Mountains REE-bearing episyenites (abs.): Society of Economic Geology*: Building Exploration Capability for the 21st Century, Program. (poster),* http://geoinfo.nmt.edu/staff/mclemore/projects/documents/Riggins_SEG.pdf*, accessed 2/3/16.*
Sheard, E.R., Williams-Jones. A.E., Heiligmann, M., Pederson, C., and Trueman, D.L., 2012, Controls on the concentration of zirconium, niobium, and the rare earth elements in the Thor Lake rare metal deposit, Northwest Territories, Canada: Economic Geology, v. 107, p. 81-104.
Sims, P.K., Stein, H.J., and Finn, C.A., 2002, New Mexico structural zone—an analog of the Colorado mineral belt: Ore Geology Reviews, v. 21, p. 211-225.
Smith, A.E., 2018, Multi-stage processes for generation of REE-enriched episyenites and fenites in New Mexico and Colorado: the role of magmatic and diagenetic fluids based on $^{40}Ar/^{39}Ar$ geochronology, whole rock geochemistry and radiogenic isotopes [M.S. thesis]: Socorro, New Mexico Institute of Mining and Technology, 352 p.
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 for a complex cooling history: New Mexico Geological Society, Guidebook 54, p. 109-117.
Suikkanen, E. and Rämö, O.T., 2019, Episyenites—charactristics, genetic constraints and mineral potential: Mining, Metallurgy, and Exploration, v. 36, p. 861-878.
Walters, A.S., Goodenough, K.M., Hughes H.S.R., Roberts, A.G., Gunn, A.G., Rushton, J., and Lacinska, A., 2013, Enrichment of rare earth elements during magmatic and post-magmatic processes; a case study for the Loch Loyal syenite complex, northern Scotland: Contributions to Mineralogy and Petrology, v. 166, p. 1177-1202.

Appendices can be found at http://nmgs.nmt.edu/repository/index.cfml?rid=2020001