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RARE EARTH ELEMENTS (REE) IN PROTEROZOIC PERALKALINE IGNEOUS ROCKS (PAJARITO MOUNTAIN) AND PEGMATITES IN NEW MEXICO

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ABSTRACT

Three types of Proterozoic deposits have economic potential for REE in New Mexico: peralkaline igneous rocks, granites, and pegmatites. The Pajarito Mountain pluton on the Mescalero Indian Reservation, south-central New Mexico is a layered, peralkaline syenitic and pegmatitic intrusion, where REE, Y and Zr predominantly occurs in magmatic eudialyte group minerals. One sample contained 6869 ppm total REE. In 1990, Molycorp, Inc. reported historic resources of 2.7 million short tons grading 0.18% Y_2O_3 and 1.2% ZrO_2. Additional areas of Proterozoic granite in New Mexico may have potential for REE deposits (Tajo Granite in Socorro County, La Cueva Granite in Taos County, and Tusas Granite in Rio Arriba County), but additional geochemical studies and ultimately drilling are needed to determine the economic potential of these areas. Pegmatites are coarse-grained igneous rocks, lenses, or veins of granitic composition that contain essential quartz and feldspar, and represent the last, most hydrous phase of crystallizing magmas. Pegmatites can contain a variety of economic commodities, including, mica, feldspar, quartz, Li, REE, Cs, Ta, Nb, Rb, Y, Sc, U, Th, Sn, B, Be and other critical minerals. Recent exploration for REE and Li has occurred in New Mexico Proterozoic pegmatites and possible nearby placer deposits in the Petaca, Ojo Caliente No. 1, and Rociada districts in northern New Mexico. Many pegmatites in New Mexico have yielded past REE production, but the REE minerals are generally scattered throughout the pegmatite and are difficult to selectively mine and process, and probably will not constitute an economic resource because of low grade, small size, and the expensive hand-sorting techniques required in order to recover any of the commodities.

INTRODUCTION

Rare earth elements (REE) are becoming increasingly more important in our technological society and are used in many of our electronic devices and energy sources. REE are used in solar panels, wind turbines, batteries, electric cars, desalination plants, and carbon capture and storage. REE is considered a critical mineral, which is defined by U.S. Presidential Executive Order No. 13817 (2017) as "*a mineral (1) identified to be a nonfuel mineral or mineral material essential to the economic and national security of the United States, (2) from a supply chain that is vulnerable to disruption, and (3) that serves an essential function in the manufacturing of a product, the absence of which would have substantial consequences for the U.S. economy or national security*". Critical minerals are mineral resources that are mostly imported into the U.S., are essential to our economy, and whose supply may be disrupted (Committee on Critical Mineral Impacts of the U.S. Economy, 2008; Schulz et al., 2017). Disruptions in supply chains can arise for any number of reasons, including natural disasters, labor strife, trade disputes, resource nationalism, conflict, and so on.

REE are mostly imported into the U.S. from China. REE include the 15 lanthanide elements (atomic number 57-71), yttrium (Y, atomic number 39), and scandium (Sc; Table 1) and are commonly divided into two chemical groups, the light REE (La through Eu) and the heavy REE (Gd through Lu and Y). REE are lithophile elements (or elements enriched in the crust) that have similar physical and chemical properties (Table 1), and, therefore, occur together in nature. The name REE is misleading; the content of the REE in the earth's crust ranges from 60 ppm for Ce to ~0.5 ppm for Tb and Lu, which is greater than the crustal abundance of silver. Four REE (Y, La, Ce, and Nd) have larger crustal abundances than lead (Naumov, 2008). However, REE are not always concentrated in easily mined economic deposits and only a few deposits in the world account for current production (Committee on Critical Mineral Impacts of the U.S. Economy, 2008; Hedrick, 2009, Long et al., 2010). Thorium (Th), uranium (U), niobium (Nb) and other elements typically are found with REE; most deposits are radioactive because of their Th and U content.

Table 1. Characteristics of rare earth elements (REE) (from Taylor and McClennan, 1985; Samson and Wood, 2005; Rudnick and Gao, 2005; Castor and Hedrick, 2006; Hedrick, 2009).

Rare Earth Element	Symbol	Oxide	Atomic Number	Abundance in the upper crust (ppm)
Scandium	Sc	Sc_2O_3	21	14
Yttrium	Y	Y_2O_3	39	21
Lanthanum	La	La_2O_3	57	31
Cerium	Ce	Ce_2O_3	58	63
Praseodymium	Pr	Pr_2O_3	59	7.1
Neodymium	Nd	Nd_2O_3	60	27
Promethium	Pm	*	61	*
Samarium	Sm	Sm_2O_3	62	4.7
Europium	Eu	Eu_2O_3	63	1.0
Gadolinium	Gd	Gd_2O_3	64	4.0
Terbium	Tb	Tb_2O_3	65	0.7
Dysprosium	Dy	Dy_2O_3	66	3.9
Holmium	Ho	Ho_2O_3	67	0.83
Erbium	Er	Er_2O_3	68	2.3
Thulium	Tm	Tm_2O_3	69	0.30
Ytterbium	Yb	Yb_2O_3	70	2.2
Lutetium	Lu	Lu_2O_3	71	0.31

* Promethium does not occur naturally.

The purposes of this report are to 1) summarize the resource potential for REE in Proterozoic rocks in New Mexico, 2) update earlier compilations by Long et al. (2010), McLemore et al. (1988a, b) and Adams (1965), and 3) suggest areas in the state for future exploration. For the purposes of this report, a REE occurrence is defined as 1) production of REE minerals, 2) whole-rock chemical analysis of approximately 1000 ppm total REE, 500 ppm Y, or 100 ppm Sc, or 3) REE-bearing minerals found in sufficient quantities to be considered a mineral resource.

Proterozoic REE deposits are found in many of the mountain ranges of New Mexico (Fig. 1) and represent a variety of tectonic settings and depositional environments. Four major periods of plutonism characterize the Proterozoic in New Mexico, including the 1) Mazatzal orogeny, 1700-1600 Ma (Karlstrom and Bowring, 1993; Karlstrom et al., 1990), 2) Late Proterozoic granitic plutonism, 1450-1350 Ma (Karlstrom and Bowring, 1993; Karlstrom et al., 1997; Karlstrom and Humphreys, 1998), 3) pre-Grenville extension and formation of continental margin at 1300-1200 Ma (Karlstrom and Humphreys, 1998), and 4) Grenville orogeny and extension during 1200-1000 Ma (Bickford et al., 2000; McLemore and Lueth, 2017).

RARE EARTH ELEMENTS (REE) IN PROTEROZOIC IGNEOUS ROCKS IN NEW MEXICO

Three types of Proterozoic deposits have potential for REE in New Mexico: peralkaline igneous rocks, granite, and pegmatites (Fig. 1). Many peralkaline igneous rocks, typically of syenite or granite composition, have higher concentrations of REE and Zr then other types of igneous rocks. Alkaline rocks are defined as rocks with Na2O+K2O>0.3718(SiO2)-14.5 (MacDonald and Katsura, 1964) or rocks with mol Na2O+mol K2O>mol Al2O3 (Shand, 1951). Peralkaline rocks are igneous rocks that are oversaturated with alkalies (Na2O+K2O), and therefore undersaturated with Al2O3. Peralkaline rocks are particularly enriched in heavy REE, Y, and Zr. Some REE and Zr deposits have been found in these rocks worldwide, but REE deposits known in these rocks are low grade (Castor, 1994). In these deposits, REE, Zr, Be, Nb, Ta, and other elements are found disseminated in the igneous rock. The Proterozoic peralkaline igneous rocks in New Mexico have not yet produced any REE. Granites are common in New Mexico Proterozoic terranes, but only a few areas have known REE occurrences (Fig. 1).
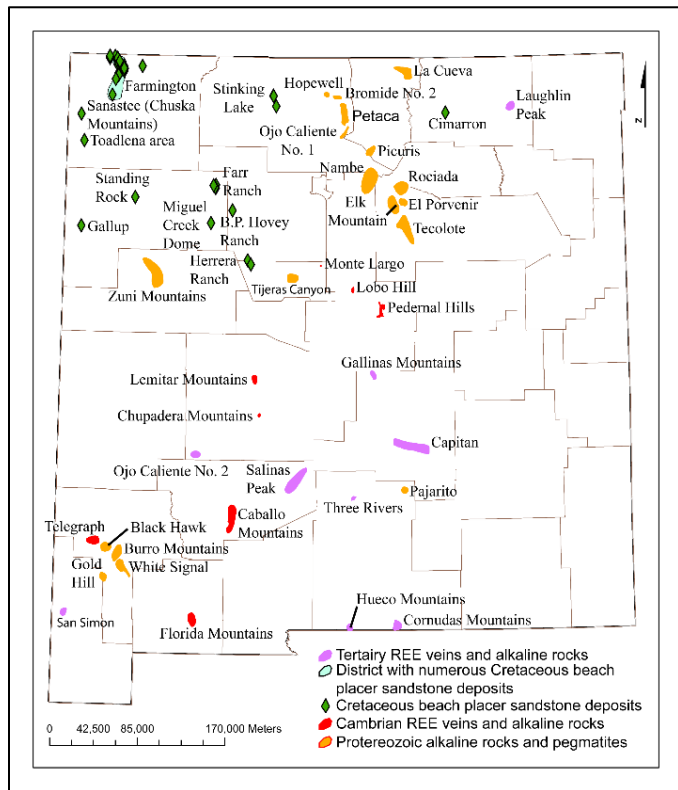

Figure 1. Mining districts in New Mexico that contain rare earth elements (REE) deposits (from McLemore and Austin, 2017). District number and summary of districts is in McLemore (2017). The Proterozoic deposits described in this report are shown in orange.

Pegmatites are coarse-grained igneous rocks, lenses, or veins with granitic composition, contains essential quartz and feldspar, and represent the last and most hydrous phase of crystallizing magmas (Page and Page, 2000; Ercit, 2005; McLemore and Lueth, 2017). Complex pegmatites include mineralogical and/or textural zones. Pegmatites can contain a variety of economic minerals, including, mica, quartz, feldspar, Li, REE, Cs, Ta, Nb, Rb, Y, Sc, U, Th, Sn, B, Be and others. A number of pegmatites in New Mexico have yielded REE production in the past (Table 2), but in general pegmatites are poor mining targets, because the REE minerals are generally scattered throughout the pegmatite and are difficult to selectively mine and process.

Table 2. REE production from Proterozoic pegmatite deposits in New Mexico (Jahns, 1946a, 1953; Holmquist, 1946; Gillerman, 1964; Parker, 1965; Bingler, 1968; Robertson, 1976; McLemore, 1983a).

District Number	Name	Production
DIS148	Petaca district	112 lbs of samarskite, few hundred lbs of monazite, 12,000 lbs of Ta-Nb-REE ore
DIS162	Elk Mountain-Spring Mountain	500 lbs of Ta-U-REE concentrate
DIS164	Rociada	Several thousand tons of REE-Ta ore
DIS166	Tecolote	$10,000 worth of beryl, tantalite-columbite and monazite
DIS058	Gold Hill	Unknown production in 1950s

REE IN PERALKALINE IGNEOUS ROCKS

Proterozoic Pajarito Mountain

Disseminated REE-Y-Zr deposits in alkaline rocks are found at Pajarito Mountain, in the northeastern part of the Mescalero Apache Indian Reservation, south of Ruidoso, Otero County (Fig. 2; Kelley, 1968; Sherer, 1990; McLemore, 1990a, 1991). Molycorp, Inc. (a former subsidiary of Unocal Corp., now Chevron Inc.) began exploration in the area in 1984 and announced the discovery of a Y and Zr deposit at Pajarito Mountain in 1989 (Sherer, 1990; McLemore, 1990a, 1991). A joint leasing-operating agreement was reached between Molycorp, Inc. and the Mescalero Apache Tribe and a recoverable resource of 2.7 million short tons grading 0.18% Y_2O_3 and 1.2% ZrO_2 as disseminated eudialyte was reported (Sherer, 1990). However, before mine planning began, a market slump in Y and Zr occurred and Molycorp, Inc. dropped the project, partly because the company was also undergoing corporate financial difficulties. The Pajarito Mountain deposit would have been the first and only deposit in the world mined solely for Y and Zr, which are typically produced as co-products or by-products of mining other commodities. More recent studies have shown high concentrations of REE as well (Appendix 1; Berger, 2018; this report).

Crystalline rocks of Proterozoic age at Pajarito Mountain were first reported by Kelley (1968). After detailed mapping and petrographic studies, Motts and Gaul (1960) presented compelling arguments for a Tertiary age of the complex, but subsequent isotopic dating confirm a Proterozoic age of about 1150-1200 Ma (Kelley, 1968; Moore et al., 1988a, b; Bauer and Pollock, 1993). The complex lies in the southern portion of anorogenic, middle Proterozoic, plutonic magmatism that extends across North America and is associated with a period (1000-1260 Ma) of mafic, volcanic, and A-type granitic intrusions in Texas and Arizona, coincident with the Grenville orogeny and subsequent extension (Anderson, 1983; Woolley, 1987; Barnes et al., 1999; McLemore et al., 2000; Bickford et al., 2000).

The Parajito Mountain complex consists of an unusual lithologic assemblage for Proterozoic rocks in New Mexico, in that the complex is predominantly alkaline, with several varieties of layered syenite, quartz syenite, nepheline syenite, alkali granite, and gabbro that are intruded by alkaline pegmatite and gabbroic dikes (Fig. 2; Kelley, 1968; Condie and Budding, 1979; Foord et al., 1983; Moore et al., 1988a; Sherer, 1990; Berger, 2018). Such rocks, although present locally, are not common lithologies in most Proterozoic terranes in New Mexico. Paleozoic sedimentary rocks unconformably overlie the Proterozoic rocks.

Berger (2018) describes several processes involved in the origin of the Parajito Mountain layered syenite complex, including three major magma pulses, crystal separation and accumulation, and interaction of the layered complex with evolving melts. The mineralogy of the alkaline rocks consists of various amounts of essential K-feldspar, plagioclase, arfvedsonite and accessory riebeckite, quartz, eudialtye, fluorite, monazite, apatite, biotite, rutile, titanite, aegirine-augite, Zr silicates, lanthanide and Y minerals, and zircon (Moore et al., 1988a; Sherer, 1990; Berger, 2018). Magmatic minerals are replaced by secondary minerals formed during late stage alteration (Berger, 2018).

Eudialyte $[(Na,Ca)_5(Zr,Fe,Mn)(Si_6O_{17})(O,Oh,Cl)]$ the major ore mineral at Parajito Mountain, is disseminated throughout the syenite,

quartz syenite, and alkali granite. Eudialyte is a zirconium silicate containing yttrium and is generally amenable to heap-leach recovery after crushing, similar to the process used in recovering gold and silver.
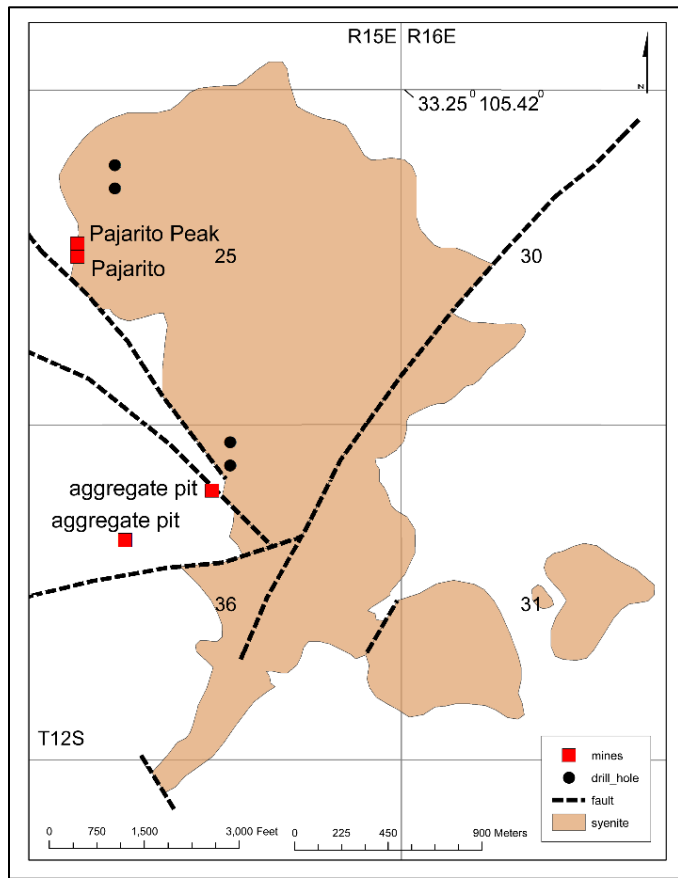

Figure 2. Generalized geology of the REE-Y-Zr deposit at Parajito Mountain, Otero County (Kelley, 1968; Moore et al., 1988b; Sherer, 1990; Berger, 2018). Locations of drill holes is approximate from Berger (2018).

Selected chemical analyses indicate the syenitic rocks are anonymously high in light-REE (Fig. 3; Appendix 1): La as high as 1500 ppm, Ce as high as 3910 ppm, (Berger, 2018; this report), and niobium (200 ppm; Moore et al., 1988a). Stream sediments in the arroyos draining the Proterozoic rocks are high in Zr (as much as 707 ppm), Y (as much as 106 ppm), and Ce (as much as 138 ppm). Additional detailed petrographic and geochemical studies, along with geophysical studies and confirmation drilling, are needed to determine if some of these commodities can be economic in the future. The deposit is at shallow depths and open pit mining was planned (Sherer, 1990). Future exploration and development of this resource is dependent upon the Mescalero's interest in exploration and mining of the deposits and the ever changing market and demand for REE, Y and Zr.

La Cueva district, Taos County
REE-Th-U veins and pegmatites (U, Th, REE, Be, mica) are associated with the southern part of the Proterozoic Costilla granitic massif in La Cueva district (also known as Vermejo Park and Costilla Creek) near Costilla Creek (Fig. 4; Reid et al., 1980; Zelenka, 1984; Goodknight and Dexter, 1984b; Lipman and Reed, 1989; McLemore, 1990b; McDonnell, 1992). The Costilla massif consists of granite gneiss, pegmatitic granite, and granite. A U-Pb zircon upper-intercept concordia age of 1644 Ma is interpreted as the age of emplacement (Lipman and Reed, 1989). Radioactive pegmatites intrude the granite and both intrude a complex Proterozoic metamorphic terrain of metamorphic and igneous rocks (McKinlay, 1956; Lipman and Reed, 1989). The Proterozoic rocks are overlain by Tertiary volcanic and

volcaniclastic rocks related to the Questa caldera to the south and the Rio Grande rift. The granitic rocks are subalkaline, metaluminous to peraluminous. Uranium mineralization in the district was discovered in the 1950s during prospecting for radioactive veins and pegmatites, and exploration was carried out in the 1970s and 1980s by Phillips Petroleum Company and Duval Corporation.
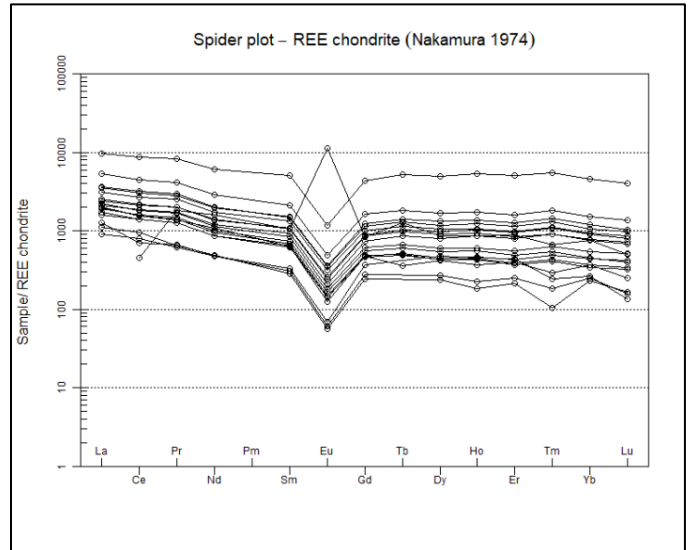

Figure 3. REE chondrite-normalized plot of samples from the Pajarito Mountain deposit, Otero County (Appendix 1). Note the enriched light REE pattern. Chondrite values from Nakamura (1974).
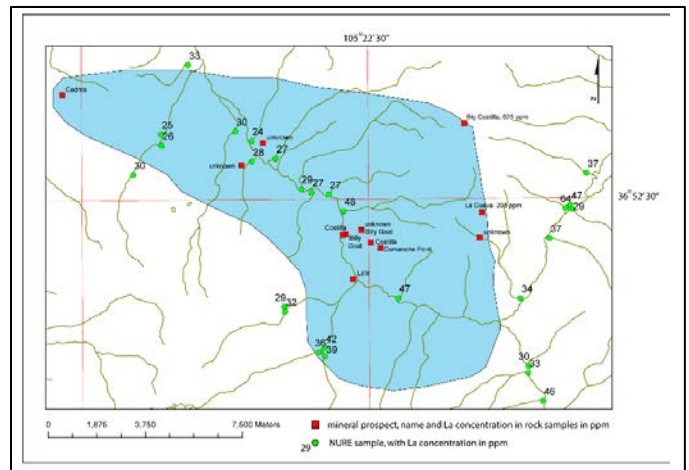

Figure 4. La geochemical map showing NURE stream-sediment locations (green) and mineral prospects (red) in the La Cueva district (blue; T30, 31N, R15E), Taos County, New Mexico. Concentrations greater than 42 ppm La (mean plus 1 standard deviation) are anomalously high. The La anomalies in stream sediments are downstream of several identified uranium-REE prospects.

Mineralized zones at the surface contain U, Th and REE minerals along fractures and in veins and pegmatites, including zircon, uraniferous magnetite, allanite, uranothorite, thorite, uraninite, thorgummite, uranophane, and uranium-bearing hematite containing as much as 1560 ppm Ce and 625 ppm La (Zelenka, 1984). Clay-rich zones at the La Cueva prospect contain uranophane and thorogummite and as much as 1643 ppm Th and 1522 U in selected samples (Zelenka, 1984).

Tajo Granite, Chupadero district, Socorro County
The Rocky Mountain Energy Co. found uranium and REE along fractures and joints in weathered and altered Tajo granite of Proterozoic age, which they called the Arroyo project (McLemore, 1983a, b). Six outliers of medium- to coarse-grained granite (formerly

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termed quartz monzonite) are exposed along north-trending faults in the Quebradas area and most contain radioactive zones (McLemore, 1983a). Pegmatite and aplite dikes are rare. Purple fluorite, hematitization and silicification are associated with northwest- to north-east-trending, radioactive, U-rich fracture zones in the granite (McLemore, 1983a, b). A sample collected for this project contained as much as 262 ppm U and 282 total REE (Appendix 1). Younger barite-fluorite-galena veins are found along the fault contacts of the exposures.

The chemical composition of the mineralized Tajo granite is unusual for Proterozoic granites in New Mexico (McLemore, 1983b). The Tajo granite is grossly similar in major-element chemistry to high-Si and high-K granites in the state (Condie and Budding, 1979). The Tajo granite is enriched in Rb, U, and Th and depleted in CaO, Na_2O, Al_2O_3, and Sr, relative to most Precambrian granites (Condie and Budding, 1979; McLemore, 1983b). This is due in part to silicification and hematitization related to the uranium mineralization. However, the chemical trends in the Tajo granite are different from chemical trends observed in altered Proterozoic granites in New Mexico. Most Proterozoic granites in New Mexico that are altered by albitization and epidotization, are enriched in Na_2O, CaO, and Fe_2O_3 and depleted in K_2O, Rb, Sr, TiO_2, and Al_2O_3, relative to unaltered granites (Condie and Budding, 1979).

The U and REE potential of the Tajo granite is uncertain. A chemical analyses is in Appendix 1. The U-Th-REE deposits in the Tajo Granite may be similar to the Bokan Mountain U-Th-REE deposits of Alaska that contain significant structurally-controlled U, Th, and REE (MacKevett, 1963; Thompson, 1988; Long et al., 2010). Additional geochemical studies and additional drilling of the Tajo Granite are needed to determine the economic potential of the U-Th-REE deposits.

Other Proterozoic granitic complexes

More than 200 uranium occurrences are found in igneous and metamorphic rocks (pegmatites, alkaline rocks, granitic rocks, carbonatites, and caldera-related volcanogenic deposits) in New Mexico, but most in New Mexico are probably uneconomic (McLemore, 1983b; McLemore and Chenoweth, 2017). A few areas have REE potential but additional studies are required to evaluate their economic potential.

Uranium-Th-REE occurrences are found in and surrounding the Tusas Mountain Granite in the Bromide No. 2 district, Taos County, in three distinct types: 1) quartz-fluorite veins and disseminations in both granite and schist along the contact between the Tusas Mountain Granite and older Moppin Metavolcanic Complex, 2) along fractures, shear zones, and faults within altered Tusas Mountain Granite, and 3) along boundaries and fractures of amphibolite-schist xenoliths and roof pendants in the Tusas Mountain Granite (McLemore, 2011). These veins, disseminations, and fracture coatings and fillings locally contain uraninite, sabugalite, meta-torbernite, thorite, huttonite, uranothorite, thorogummite, zircon, monazite, xenotime, and allanite (Bingler, 1968; Chenoweth, 1974; Goodknight and Dexter, 1984a; McLemore et al., 1988a, b; McLemore, 2011). Alteration, specifically silicification and epidotization, forms a thin halo along both sides of the veins and mineralized rocks. Hydrothermal brecciation and hydrofracturing are common textures. Chemical analyses of samples contain as much as 0.17% U_3O_8 and 2% Th and anomalous high concentrations of Nb (720 ppm) and La (580 ppm) are present in some samples (McLemore, 1983a; Goodknight and Dexter, 1984a). More mineralogic and chemical analyses, especially REE, are needed to determine the potential for these other commodities.

REE IN PROTEROZOIC PEGMATITE DEPOSITS

Most of the pegmatites found in New Mexico are associated with the Late Proterozoic granite plutonism of 1450–1400 Ma, although some possibly may be as young as 1100-1200 Ma. The pegmatites in New Mexico vary in size, but are typically several hundred meters long and several tens of meters wide. Simple pegmatites consist of feldspar, quartz, and mica, whereas complex pegmatites are mineralogically and texturally zoned and consist of a variety of rare minerals. Several commodities have been produced from complex pegmatites in New Mexico in the past; including mica, quartz, feldspar,

beryl, Li, U, Th, REE, Nb, Ta, W, and gem stones. At least 75 pegmatites in New Mexico contain REE, Nb, and Th. Additional commodities occur in pegmatites that could be recovered, including Sb, Rb, and Mo (Jahns, 1946a; McLemore et al., 1988a, b; McLemore and Chenoweth, 2017). Chemical analyses of selected pegmatites are in Appendix 1; REE are shown in Figure 5. Recent exploration for REE and Li has occurred in New Mexico pegmatites and possible nearby placer deposits in the Petaca, Ojo Caliente No. 1, and Rociada districts in northern New Mexico. Typically minerals containing these rare commodities are scattered discontinuously throughout the pegmatite, thereby hampering economic recovery.
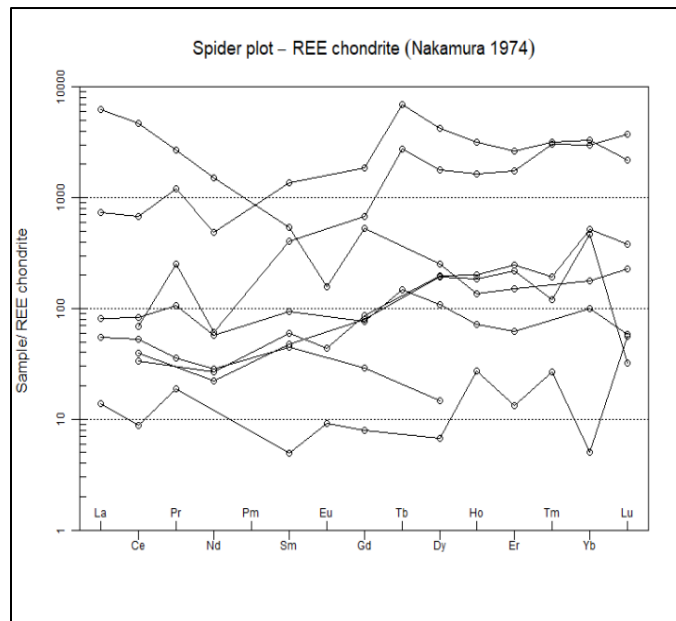

Figure 5. REE chondrite-normalized plot of pegmatites samples from New Mexico (Appendix 1). Note the enriched light REE pattern. Chondrite values from Nakamura (1974).

Nearly all of the pegmatites in New Mexico are Proterozoic in age and intruded metamorphic and granitic rocks; mid-Tertiary pegmatites are found in the Organ Mountains, Black Range (Carpenter district) and Burro Mountains. Most pegmatites in New Mexico, especially the mid-Tertiary pegmatites, probably will not constitute an economic resource because of low grade, small size, and the expensive hand-sorting techniques required in order to recover any of the commodities.

Ojo Caliente No. 1 and Petaca districts, Rio Arriba County

The predominant mineral deposits found in the Ojo Caliente No. 1 and Petaca districts are pegmatites (Fig. 2; Appendix 1). All of the pegmatites in these districts are Proterozoic in age and intrude metamorphic and granitic rocks. Mica, feldspar, beryl, uranium, and other commodities have been produced from these pegmatites (Table 4; Bingler, 1968; Chenoweth, 1974).

There are three general types of pegmatites in the Petaca and Ojo Caliente No. 1 districts: 1) small, irregular, homogeneous, mineralogically simple pegmatites cutting granites, 2) irregular pegmatite dikes with complex mineralogies that roughly parallel foliation in the metamorphic rocks (sills and strike dikes of Jahns, 1946a), and 3) irregular pegmatite bodies with complex mineralogies that crosscut foliation in metamorphic rocks (Just, 1937; Jahns, 1974). The pegmatites average 1100 m long and 1 m wide. The paragenesis differs for each pegmatite, suggesting that the pegmatites were crystallized from variable solutions. Accessory minerals typically are found in the intermediate and central core zone of the pegmatites. REE is found mostly in the albite-rich zones and in fractures within the quartz cores. Stream-sediment samples collected from the Ojo Caliente drainage basin range from <10 to 140 ppm La and 1 to 150 ppm Ce. U-Pb zircon dating places the age of crystallization of the pegmatites at ~1400 Ma (Koning et al., 2007).

Table 4. Production from the Petaca and Ojo Caliente No. 1 mining districts, Rio Arriba County (from Jahns, 1946a; Meeves et al., 1966; McLemore, 1990a; NMBGMR files). w=production data withheld.

Commodity	Production	Years of production
Beryl	12,748	
Columbite-tantalite (lbs)	5,092-12,000	
Sheet mica (lbs)	604,927	
Scrap mica (short tons)	15,191	1899-1963
Feldspar	w	
Lithium (short tons)	w	1920-1963
Bismuth (lbs)	100	1943
Rare earth elements (samarskite) (lbs)	5,000	
Kyanite (short tons)	1,500	1928
Uranium	2 lbs	1954

Nambe district

The Nambe district is in the Truchas Range, Rio Arriba and Santa Fe Counties. Several northeast-trending pegmatites intruded the Proterozoic rocks, are up to a meter wide and few tens of meters long, and consist of quartz, microcline, perthite, plagioclase, muscovite, tourmaline, garnet, magnetite-ilmenite, and other minerals. Approximately 1500 lbs of beryl was produced from the Fish deposit (NMRA0155) in 1957 (Redmond, 1961). The Fish pegmatite is approximately 30 m long, 3 m wide, strikes N80°W, dips 80°S, and consists of feldspar, quartz, muscovite, and beryl.

Picuris district

The Picuris district, in the Picuris Range of the Sangre de Cristo Mountains (Fig. 1) is best known for the Harding pegmatite, a Proterozoic complex zoned pegmatite, which has produced substantial amounts of beryl, lepidolite, spodumene, and tantalum-niobium (microlite) minerals. The pegmatite was discovered about 1910 and mining for lepidolite began in 1919. This was the first of three mining periods at the pegmatite (the Lepidolite period, 1919-1930) (Jahns and Ewing, 1977). Lepidolite, a Li-bearing mica, is used to manufacture glass. Today, Li is a major component of some batteries. From 1920 to 1930, approximately 12,000 short tons of lepidolite-spodumene ore, averaging 3.5% LiO_2 was produced (Schilling, 1960). Additional production occurred in 1942-1947 (41 short tons of spodumene, 558 short tons of lepidolite) and again in 1950-1953 (806 short tons of lepidolite, 249 short tons of spodumene). The Harding pegmatite is actually a series of granitic pegmatites in a well-defined belt 710 m long and 50-170 m wide that consists of numerous pinch-and-swell pegmatite dikes, 1-3 m thick (Jahns and Ewing, 1977).

The second period of mining, the Microlite period (1942-1947), began in 1942 when Arthur Montgomery began mining microlite, a tantalum-niobium mineral. The Harding pegmatite is one of the few mines in the world to produce microlite. From 1942 to 1947, more than 22,000 pounds of tantalum concentrates, averaging 68% Ta_2O_5 and 7% Nb_2O_5, were produced (Jahns and Ewing, 1977). In addition, 464 pounds of placer tantalite and columbite (43% Ta_2O_5, 36% Cb_2O_5) were produced.

The third mining period, the Beryl period, occurred between 1950 and 1958. From 1950 to 1959, 848.3 short tons of beryl that averaged 10% BeO were produced from the Harding pegmatite, and from 1950 to 1955 the pegmatite accounted for nearly 20% of the beryl production in the United States (Schilling, 1960). After mining ceased in 1959, the Harding mine was leased to several companies for exploration of additional resources. Since the early 1970s, the mine has been leased and subsequently donated to the University of New Mexico for scientific preservation.

Elk Mountain-Spring Mountain district

Elk Mountain district is in the southern Sangre de Cristo Mountains, where pegmatites intruded Proterozoic quartz-mica schist (Jahns, 1946a; Redmon, 1961). The north-trending, undulatory Elk Mountain pegmatite is approximately 70 m long and 30 m wide and consists of microcline, quartz, muscovite, garnet, fluorite, tourmaline, columbite, and trace beryl, gadolinite and autunite, euxenite, uranophane and other REE minerals (Redmon, 1961; Northrop, 1996). NURE stream sediments in a drainage near the Sparks-Stone pegmatite contain anonymously high concentrations of Ce (as much as 619 ppm), La (as much as 307 ppm), Th (as much as 113 ppm), and U (as much as 20.5 ppm), and other REE. The Sparks Stone pegmatite yielded 15 short tons ore that yielded 32 lbs U_3O_8 (grade of 0.11% U_3O_8) in 1955-1956.

Rociada district

The Rociada mining district is in the eastern Sangre de Cristo Mountains, east of the Pecos Wilderness Area. The pegmatites intruded amphibolite, are a few centimeters to more than 7 m wide and as much as 50 m long, and consist of quartz, perthite, albite, lepidolite, and muscovite (Lane, 1980). Rhabdophanite is reported by Redmon (1961). Approximately, 372 short tons of lepidolite and 1.5 short tons of microlite were produced from the Pidlite mine (Sheffer and Goldsmith, 1969). The pegmatite is 25 m long, 6 m wide, intrudes schist, and consists of quartz, microcline, microlite, lepidolite, beryl and other rare minerals, including betafite, monazite, and cyrtolite (Jahns, 1953, table 1; Northrop, 1996). REE are present in the outer zones of the pegmatite.

Tecolote district

The Tecolote district is in the Rincon Range, where 24 short tons of beryl was produced from the Priest mine (Redmon, 1961). The Priest pegmatite intruded Proterozoic schist and gneissic granite, is 330 m long and 30 m wide, and consists of quartz, microcline, columbite, garnet, tourmaline, sericite, and beryl.

Mora district

The Mora pegmatite was mined in 1949-1952 for mica by the Great Western Mining Co. (Jahns, 1946b) The pegmatite is approximately 100 m long, 40 m wide with a quartz core (13 m wide), intermediate zone of perthite and mica (0.6 m wide) and outer zone of orthoclase and quartz (0.6 m).

Table 5. Scrap mica production from the Mora pegmatite (Everett, 1952).

Year	Scrap mica (tons)	Value
1949	40	1300
1950	334	10320
1951	1500	45000
1952	700	28000
Total	2574	84620

Gold Hill district

The Gold Hill district is in the Burro Mountains (Fig. 2), which is a northwest-trending range of predominantly Proterozoic Burro Mountains Granite (1550 Ma; Hedlund, 1978), surrounded by Quaternary alluvial fans on the west end and by Tertiary volcanic rocks on the east end. Proterozoic pegmatites intruded the Burro Mountain granite and some of these pegmatites were prospected in the 1950s for U and Th. The oldest rocks in the district form the Bullard Peak Group of Hewitt (1959) and consist of migmatite, quartz-biotite gneiss, hornblende gneiss, and amphibolites. This intrusive episode was followed by a pervasive retrograde event in which the mafic rocks were chloritized, sericitized, and epidotized. Proterozoic diabase dikes and plugs were subsequently intruded. These rocks are fractured and intruded by basaltic, rhyolite and felsic dikes.

The REE-Th-U pegmatites in the district occur in the Burro Mountains granite (McLemore et al., 1988a, b). They vary in size from pods a few inches across to lens-shaped bodies several hundred feet long and almost as wide. Two veins 0.7 m wide and 16 m long have been located. Minerals in the pegmatites include quartz, microcline, albite, muscovite, biotite, magnetite, garnet, fluorapatite, REE-bearing minerals, such as allanite, euxenite, samarkite, and cyrtolite. Thorium,

niobium, tantalum, U, REE, and beryllium are present. One of the veins contains 0.05 to 0.72% Th. The pegmatites are zoned with coarse quartz at the core with small segregations of microcline (Kelley and Branson, 1947; Gillerman, 1964). Surrounding the core is a quartz-perthite zone with muscovite and biotite. The next zone out is a quartz-albite-muscovite or quartz-albite-microcline zone. The outermost zone is quartz-microcline. At the South pegmatite, massive green fluorite occurs in the quartz-albite-muscovite zone.

SUMMARY

The best potential for REE deposits in Proterozoic rocks in New Mexico are disseminated REE-Y-Zr deposits in alkaline rocks found at Pajarito Mountain, Otero County. Additional areas of Proterozoic granite (Tajo Granite in Socorro County, La Cueva Granite in Taos County, and Tusas Granite in Rio Arriba County) may have potential for REE deposits, but additional geochemical studies and ultimately drilling are needed to determine the economic potential of these areas. Most pegmatites in New Mexico, especially the mid-Tertiary pegmatites, probably will not constitute an economic resource because of low grade, small size, and the expensive hand-sorting techniques required in order to recover any of the commodities.

ACKNOWLEDGMENTS

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APPENDIX

Appendix 1. Selected trace chemical analyses in parts per million (ppm) of pegmatites and Proterozoic granites and syenites in New Mexico. Samples from NMBGMR are by NMBGMR Chemistry Laboratory by Induced coupled plasma spectroscopy in 1996-2000.

sample	name	type	Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	U	Th	Nb	Zr	Source
2383	Nambe	pegmatite	545	243	583	134	310	278		512	323	1455	221	595	95	720	75	1092	610			NMBGMR
2384	Miller	pegmatite	33	27	72	12	36	19		21	7	37	5	14		22	2	183	279			NMBGMR
2385	Globe	pegmatite	600		59	28	38	82		186	128	606	114	396	92	660	128	242		649		NMBGMR
2389	Alto	pegmatite	14	18	46	4	18	9		8		5										NMBGMR
4543	White Top A	pegmatite	161		29		17	12	3.4	24		68	14	55	5.8	113	13	12	70			NMBGMR
4544	White Top B	pegmatite	138		34		14	9.7		22		66	13	49	3.6	103	1.1	26	80			NMBGMR
2736	Harding	pegmatite	3.1	4.6	7.6	2.1		1	0.7	2.2		2.3	1.9	3	0.8	1.1	1.9	<5	<5			NMBGMR
1784	McCory	pegmatite	372	2057	4060	303	954	110	12	146		87	9.6	34		39	7.7	200	217			NMBGMR
2743	1Tajo ore pile	granite	292	52	143	7.9	64	2.3	5.5	77		47	14	34		32	6.4	445	20	31		NMBGMR
4789	Par1	Pajarito syenite	510	300	682	69	297	63	4.7	77		92	16	57	5.5	55	5.4					NMBGMR
4790	Par2	Pajarito syenite	491	372	834	73	308	58	4.3	67		82	13	48	3.1	51	5.7					NMBGMR
4791	Par3	Pajarito syenite	1230	422	601	74	298	67	5.3	102		163	32	100	7.3	58	4.6					NMBGMR
4792	Par4	Pajarito syenite	694	662	1340	155	687	129	9.7	133	17	145	26	89	8.8	81	8.5					NMBGMR
4583	Pajarito	Pajarito syenite	3140		390	204	1010	212	865	234	60	293	60	199	20	165	17					NMBGMR
PM5-257.25 GC	QM EASC	Pajarito syenite	1959	1020	2330	282	1100	273	24.1	280	53.2	359	74.3	221	33.1	206	29.4	21.9	109	310	12050	Berger (2018)
PM5-297.83 GC	EASC MA	Pajarito syenite	1155	742	1590	188	715	171	14.1	171	31	205	42.1	124	18.8	120	17.3	21.9	37	244	6921	Berger (2018)
PM-311.75 GC	EASC HA	Pajarito syenite	895	531	1200	143	541	130	10.8	130	23.9	155	32.1	95.7	14.8	96.1	14.2	12.7	55.4	230	5679	Berger (2018)
PM5-367.42 GC	ESC	Pajarito syenite	3402	1750	3870	467	1800	435	37.6	454	84.7	577	122	360	54.3	335	46	14.4	18.5	656	21260	Berger (2018)
PM1-384.92 GC	ESC band	Pajarito syenite	2006	927	2140	252	978	246	21.3	272	51.3	351	74.4	219	32.7	200	28.6	36.6	287	561	13280	Berger (2018)
PM3-91.18 GC	ESC band	Pajarito syenite	2283	1200	2790	332	1260	302	27.2	319	60.4	402	86.7	260	38.6	235	33.1	15.5	14.4	739	15010	Berger (2018)
PM3-255 GC	EASC MA	Pajarito syenite	1503	703	1600	195	762	190	16.2	206	40.7	275	60.5	181	27.2	170	24.3	12	48.9	372	7929	Berger (2018)
PM3-330.75 GC	ESC HG	Pajarito syenite	9184	3160	7570	935	3860	1020	90.2	1190	246	1700	379	1130	166	1010	136	16.8	12.1	2210	55270	Berger (2018)
PM3-343.92 GC	EASC CG	Pajarito syenite	1751	840	1900	227	877	217	18.7	240	46.1	309	65.3	189	27.2	167	23	22.4	35.9	480	9273	Berger (2018)
PM3-418.92 GC	EASC HA	Pajarito syenite	503	306	693	83.5	318	73.5	6.19	72.9	12.9	85.1	17.9	54.7	8.94	63.8	9.99	5.9	43.6	87	3095	Berger (2018)
PM3-435 GC	ESC	Pajarito syenite	1709	797	1840	224	866	222	19.8	245	48	333	71.5	214	32.4	201	26.8	9.1	12.4	386	8767	Berger (2018)
PM3-445 GC	ESC	Pajarito syenite	2396	1180	2630	315	1240	308	27.5	344	66.2	454	96.6	288	43.7	264	35.2	10.5	19	555	11750	Berger (2018)
PM5-92.18 GC	PEASQ	Pajarito syenite	875	639	1360	159	598	137	11.6	134	23.5	149	29.7	83.6	12.3	75.8	10.9	15.5	76.7	209	5574	Berger (2018)
PM1-489.67	PEAS	Pajarito syenite	807	567	1220	142	539	125	10.9	128	22.8	149	30.5	88.3	13	81.1	11.7	13.4	71.1	351	6268	Berger (2018)
PM3-56.13 GC	PEAS	Pajarito syenite	985	629	1390	164	633	149	12.9	155	28.2	185	38.4	110	16.2	98.6	13.5	15.6	73	258	7135	Berger (2018)
PM5-348.83 GC	PAAS	Pajarito syenite	174	120	268	33.2	134	27	2.14	25.4	4	24.9	5.3	16.7	2.88	22.5	3.87	1.3	6.1	73	675	Berger (2018)