GEOCHEMISTRY OF FOUR RARE EARTH ELEMENTS (REE) DEPOSITS IN NEW MEXICO

Virginia T. McLemore [1]

[1]New Mexico Bureau of Geology and Mineral Resources (NMBGMR), New Mexico Institute of Mining and Technology, Socorro New Mexico, 87801, 575-835-5521, ginger@nmbg.nmt.edu

Introduction

Lindgren (1933) was one of the first geologists who noted that a belt of alkaline-igneous rocks extends from Alaska and British Columbia southward into New Mexico, Trans-Pecos Texas, and eastern Mexico (Fig. 1) and that these rocks contain relatively large quantities of gold, fluorine, zirconium, rare earth elements (REE), and other elements. Since then, the North American Cordilleran alkaline-igneous belt has been exploited for numerous types of mineral deposits, especially gold and REE. Deposits within this belt have produced significant amounts of gold in the United States and Canada and include Cripple Creek, Colorado (702 metric tons of gold production), Black Hills, South Dakota (235 metric tons gold production) and Landsky-Zortman, Montana. The North American Cordilleran alkaline-igneous belt is a north-south belt of alkaline igneous rocks and crustal thickening, roughly coinciding with the Great Plains physiographic margin with the Basin and Range (including the Rio Grande rift) and Rocky Mountains physiographic provinces (Mutschler et al., 1985, 1991; Bonham, 1988; Thompson, 1991a; Richards, 1995; McLemore, 1996; Jensen and Barton, 2000; Kelley and Luddington, 2002). In New Mexico, the mineral deposits found in the North American Cordilleran alkaline-igneous belt are associated with Eocene-Oligocene alkaline to calc-alkaline rocks that were called Great Plain Margin (GPM) deposits by North and McLemore (1986, 1988) and McLemore (1996, 2001). Alternative classifications by other workers include Au-Ag-Te veins (Cox and Bagby, 1986; Bliss et al., 1992; Kelley et al., 1998), alkalic-gold or alkaline-igneous related gold deposits (Fulp and Woodward, 1991; Thompson, 1991a, b; Bonham, 1988; Mutschler et al., 1985, 1991; Richards, 1995; Jensen and Barton, 2000), porphyry gold deposits (Rytuba and Cox, 1991) and the Rocky Mountain Gold Province.

With the renewed interest in REE as commodities needed for many of our technological devices, REE deposits throughout this belt are being re-examined for their economic potential. In New Mexico, the mineral deposits found in the North American Cordilleran alkaline belt are associated with Eocene-Oligocene alkaline to calc-alkaline rocks (McLemore et al., 1988a, b). Four areas in New Mexico have been examined over the last 20 years for their REE potential: Laughlin Peak, Gallinas Mountains, Capitan Mountains and Cornudas Mountains. Other districts in the North American Cordilleran alkaline belt in New Mexico are predominantly gold-and/or molybdenum-bearing districts, with minor or no REE deposits (Fig. 2; McLemore, 2015a, b).

Although many geologists have studied these four REE deposits (Table 1), no one has compared the geochemistry of both the associated igneous rocks and the mineral deposits. The purpose of this paper is to compare the geology, geochronology, geochemistry, and mineralogy of the igneous rocks and the mineral deposits in these four REE deposits in order to better understand the origin and economic potential of REE deposits. This work is part of on-going studies of mineral deposits in New Mexico and includes updates and revisions of prior work by North and McLemore (1986, 1988) and McLemore (1996, 2001, 2014, 2015).

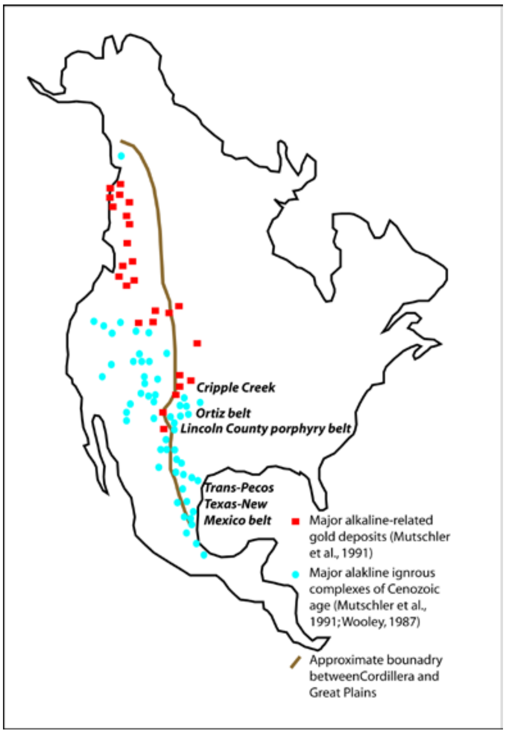


Figure 1. Extent of the North American Cordilleran alkaline belt (Woolley, 1987; Mutschler et al., 1991; McLemore, 1996).

Table 1. Summary of REE districts related to the North American Cordilleran alkaline-igneous belt in New Mexico (also known as Great Plains Margin or GPM districts). The district id number refers to the New Mexico Mines Database district number (McLemore et al., 2005a, b). Locations of districts are shown in Figure 2. Types of deposits are described in text. Associated elements are determined from mineralogy (Northrop, 1996) and chemical analyses compiled by the author. Ages in bold italics are by $^{40}Ar/^{39}Ar$ methods, other ages are predominantly by K/Ar methods.

District Id	Name	Selected elements (produced are in bold)	Age Ma(bold italics are $^{40}Ar/^{39}Ar$)	Breccia pipes	Fe skarns	Th-REE veins	Predominant mineralogy	References
DIS020	Laughlin Peak	REE, Th, U	***22.8***-32.3	x		x	Crandallite, xenotime, brookite, quartz, calcite, feldspar, barite, fluorite, rutile, zircon, pyrite	Stroud (1997), Staatz (1985, 1986, 1987), Potter (1988), Schreiner (1991)

District Id	Name	Selected elements (produced are in bold)	Age Ma(bold italics are $^{40}Ar/^{39}Ar$)	Breccia pipes	Fe skarns	Th-REE veins	Predominant mineralogy	References
DIS091	Capitan Mountains	**Fe,** REE, Th, U, Be	***28.3***		x	x	quartz, fluorite, adularia, calcite, fluorite, titanite, allanite, thorite	McLemore and Phillips (1991), Phillips et al. (1991), Allan and McLemore (1991), Campbell et al. (1995), Dunbar et al. (1996), Rawling (2011)
DIS092	Gallinas Mountains	**Cu, Ag, REE**, Th, U, Te	29.2	x	x	x	fluorite, quartz, barite, pyrite, bastnaesite, calcite, galena, bornite, chalcocite, agardite, parasite, xenotime, monazite	Perhac (1970), Korzeb and Kness (1992), Schreiner (1993), McLemore (2010), Vance (2013)
DIS128	Cornudas Mountains	REE, Th, U, Be	***36.3***	x		x	eudylite, quartz, calcite	McLemore et al. (1996), New Mexico Bureau of Mines and Mineral Resources et al. (1998), Schreiner (1994), Potter (1996)

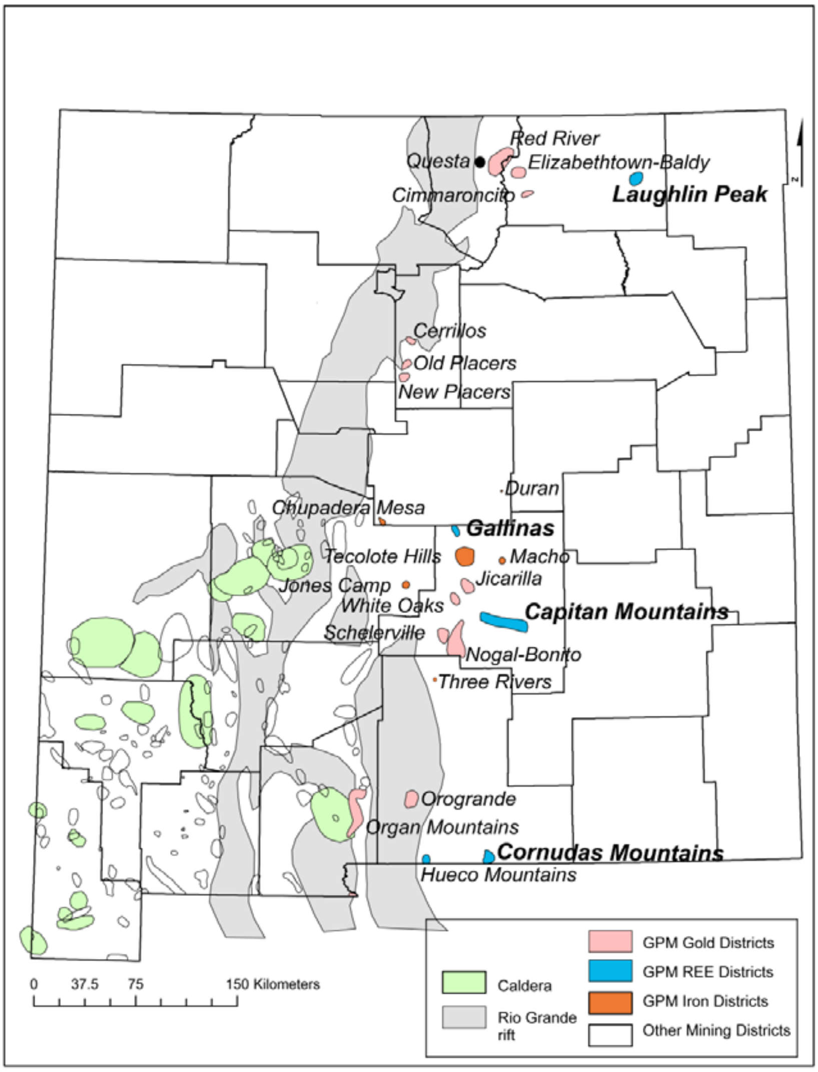


Figure 2. Mining districts related to the North American Cordilleran alkaline-igneous belt (GPM or Great Plains Margin deposits), Rio Grande rift, calderas, and other Eocene-Miocene mining districts in New Mexico (Chapin et al., 1978, 2004; McLemore, 1996, 2001; McLemore et al., 2005a, b). GPM districts are summarized in McLemore (1996, 2015a, b). REE deposits discussed in this report are in bold.

Methods of study

Data used in this report have been compiled from a literature review (references cited in Table 1), field examination, and unpublished data by the author, including mineralogy and geochemistry of the igneous rocks and the mineral deposits. Analytical methods are described in the various cited reports. Mineral and chemical compositions of igneous rocks in the GPM districts were obtained from numerous reports as cited as well as unpublished data by the author and are available upon request. The data were plotted on various geochemical and tectonic diagrams (Irvine and Baragar, 1971; Pearce et al., 1984; Frost et al., 2001; Schandl and Gordon, 2002) and compared, as described below and by McLemore (2015b). A variety of nomenclatures for the igneous rocks in these districts were used in previous studies, because the rocks typically are porphyritic in a fine-grained matrix and include shallow intrusions as well as extrusive volcanic rocks. The nomenclature of igneous rocks in this report mostly conforms to the International classification proposed by LeMaitre (1989), where the primary classification of igneous rocks is based upon mineralogy and, if too fine-grained to determine mineralogy, by the use of whole-rock geochemical analyses using the TAS (Cox et al., 1979) and R1-R2 (de la Roche et al., 1980) diagrams. Mineralized areas were examined and sampled during 1980-2013 by the author and during 1982-1993 by the U.S. Bureau of Mines and U.S. Geological Survey as part of mineral resource assessments (Tuftin, 1984; Staatz, 1985, 1986, 1987; Korzeb and Kness, 1992; Schreiner, 1991, 1993, 1994).

Age and geochemistry of associated igneous rocks

The REE deposits in New Mexico associated with Eocene to Oligocene alkaline igneous rocks are found in small- to medium-sized volcanic fields or porphyry systems, with ages ranging from 22.8 to 36.3 Ma (Table 1) and were typically emplaced as texturally zoned porphyritic plutons (Capitan and Cornudas Mountains) or compositionally complex volcanic fields (Laughlin Peak and Gallinas Mountains). Carbonatite dikes are found only in the Laughlin Peak district, although geochemical data and fenitization in the Gallinas Mountains suggest that carbonatites could occur in the subsurface (Schreiner, 1993; Vance, 2013). The igneous rocks are typically subalkaline to alkaline, metaluminous to peraluminous intrusions, with light REE-enriched patterns with or without an europium anomaly (Fig. 3, 4, 5). Igneous rocks in three of the GPM districts associated with predominantly REE deposits (Laughlin Peak, Gallinas Mountains, and Cornudas Mountains) are ferroan, alkali-calcic to alkali (according to Frost et al., 2001). Geochemically, the rocks plot as WPG (within-plate granites) to VAG (volcanic arc granites) according to Pearce et al. (1984), and active continental margins according to Schandl and Gordon (2002). Most igneous rocks plot as A-type granitoids except for the Laughlin Peak igneous rocks, which overlap the I/S and A-type granitoids (Whalen et al., 1987). Detailed geologic mapping of several districts in the North American Cordilleran alkaline-igneous belt have documented evidence of local structural control of intrusive rocks and mineral deposits (Staatz, 1986, 1987; Nutt et al., 1997; McLemore and Zimmerer, 2009). The similar compositions of GPM igneous rocks suggest that the magmas had a similar origin and were produced from similar source regions. Subtle differences are probably related to differences in fractional crystallization, especially of minerals such as garnet, zircon, and apatite, and water-rock interactions accounts for variations in K_2O, Na_2O, Ba, Rb, and Sr.

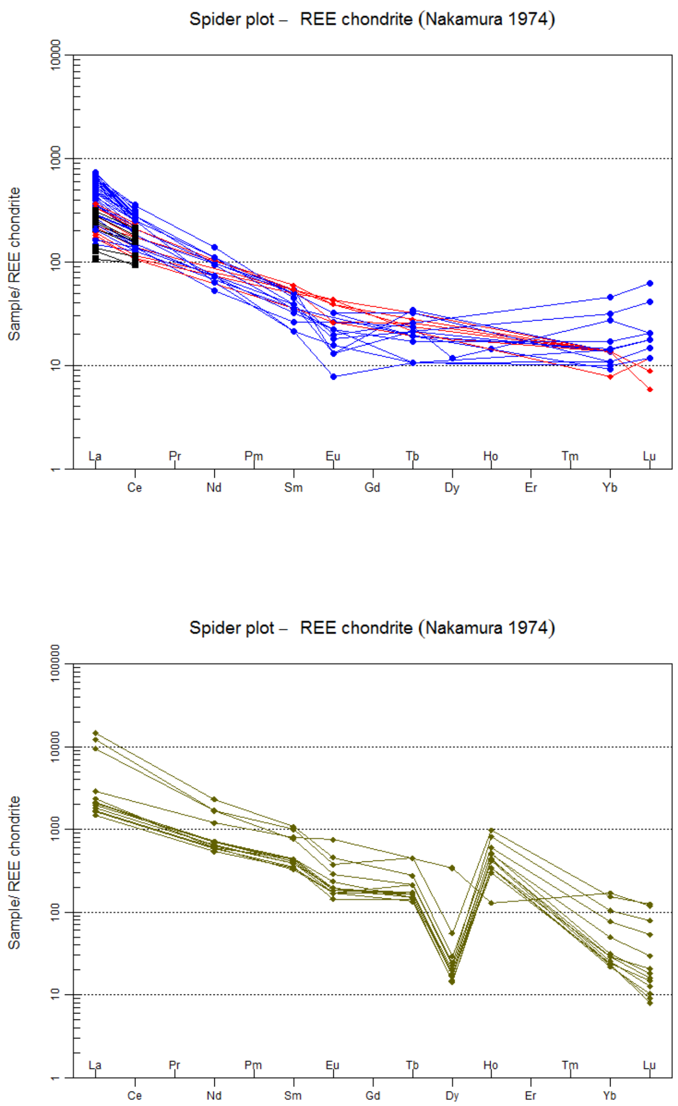


Figure 3. Chondrite-normalized (Nakamura, 1974) REE plots of igneous rocks from the Laughlin Peak district. Black squares are basalts, red diamonds lamprophyres,

blue circles phonolite and trachyte, olive green diamonds are carbonatites. Data are from Potter (1988), Schreiner (1991) and unpublished data by the author.

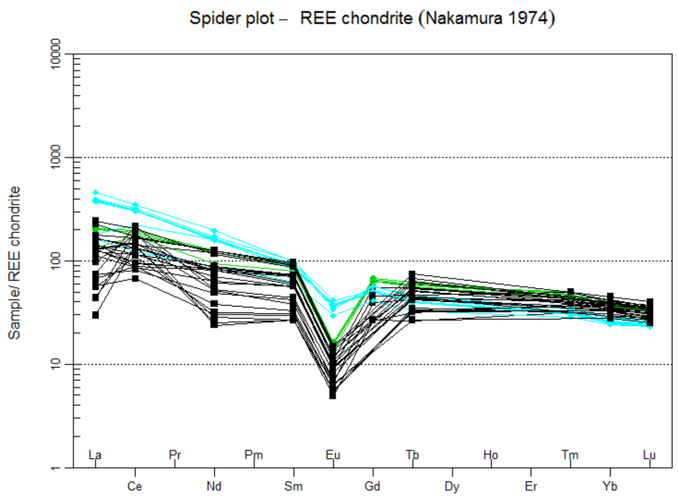


Figure 4. Chondrite-normalized (Nakamura, 1974) REE plots of igneous rocks from the Capitan Mountains. Turquoise diamonds are porphyry granite, green circles are aplite, and black squares are granophyre. Data are from Allen and McLemore (1991) and Dunbar et al. (1996).

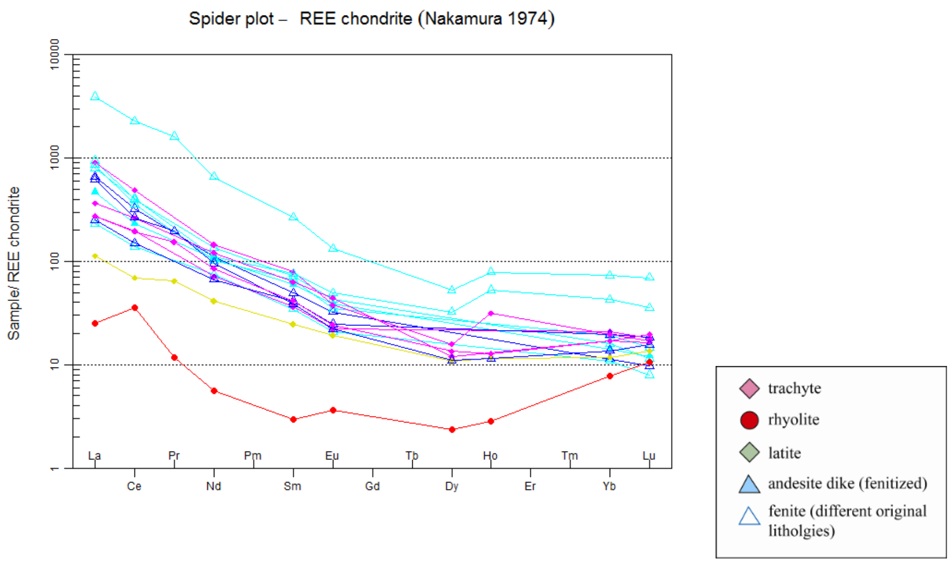


Figure 5. Chondrite-normalized (Nakamura, 1974) REE plots of igneous rocks from the Gallinas Mountains. Data are from Schreiner (1993) and McLemore (2010).

Description of REE deposits

Vein deposits are found in all four REE deposits (Table 1). Breccia pipes are found in the Laughlin Peak, Gallinas Mountains and Cornudas Mountains and iron skarns and veins with REE are found in the Capitan Mountains and Gallinas Mountains districts. Although the four districts have similar light REE enriched chondrite-normalized patterns (Fig. 6, 7, 8, 9), the REE minerals are different in each district (Table 1). The REE deposits in New Mexico are typically structurally controlled and involve mixing and cooling of magmatic meteoric waters and leaching from host rocks (Table 2). The REE deposits are typically not found with significant gold deposits, although trace amounts of gold are locally present (Tuftin, 1984; Korzeb and Kness, 1992; Schreiner, 1991, 1993, 1994; McLemore, 2010). Fluorite veins are only significant in the Gallinas districts where fluorite was produced, but fluorite is found only in small amounts in most GPM districts (McAnulty, 1979; unpublished data by the author).

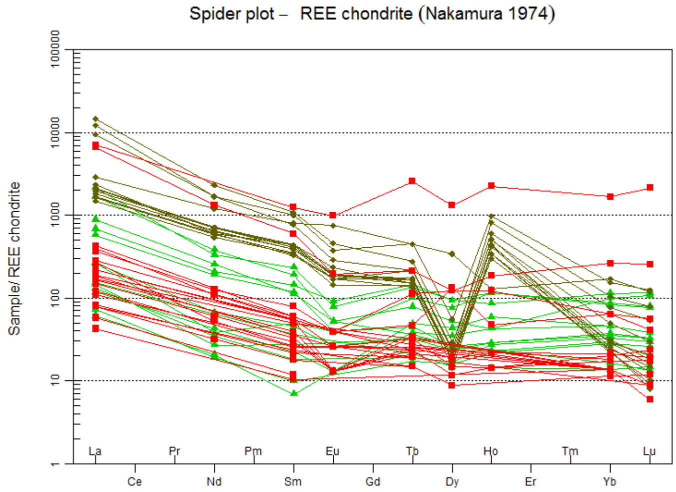


Figure 6. Chondrite-normalized (Nakamura, 1974) REE plots of veins (red squares), breccia pipes (green triangles), and carbonatites (olive green diamonds) from the Laughlin Peak district. Data are from Schreiner (1992) and unpublished data by the author.

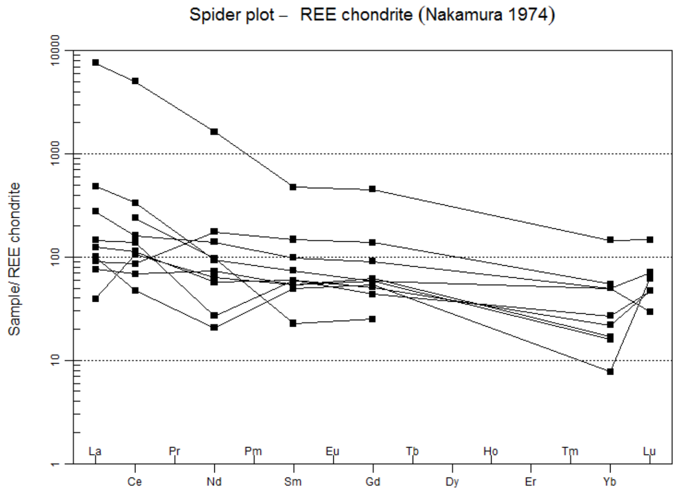
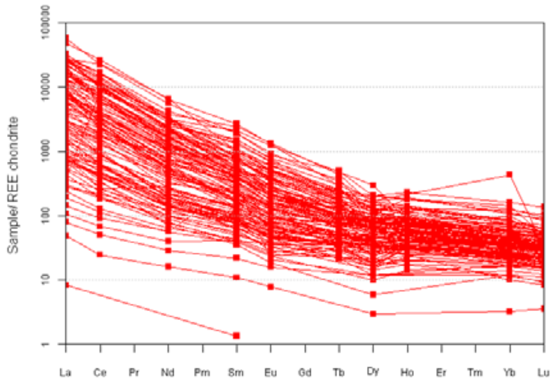
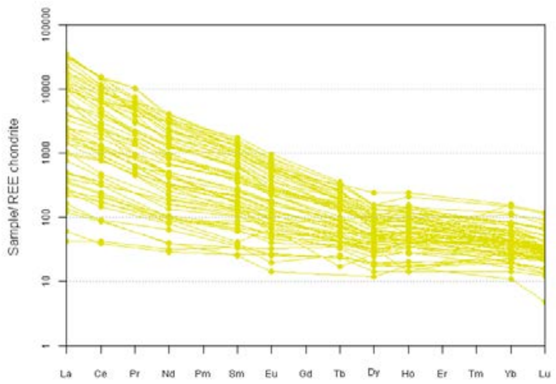


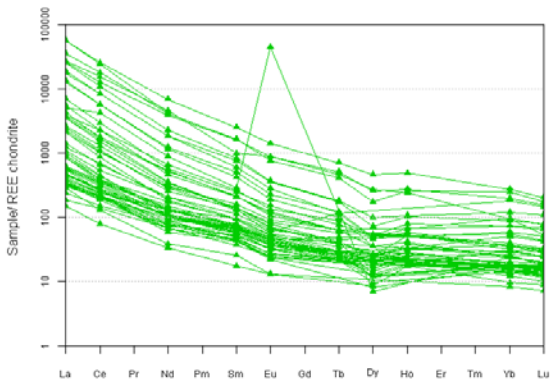
Figure 7. Chondrite-normalized (Nakamura, 1974) REE plots of igneous rocks from the Gallinas Mountains. Note that europium was not analyzed for. From unpublished data by the author.



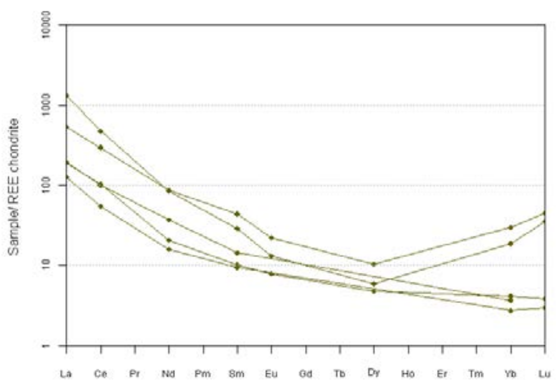
a) REE-F veins (131 samples)



b) Cu-REE-F veins (65 samples)



c) Breccia pipe deposits (58 samples)



d) iron skarns (6 samples)

Figure 8. Chondrite-normalized REE plots (Nakamura, 1974) of mineralized samples from the Gallinas Mountains. Data from Schreiner (1993) and McLemore (2010). Note the similarity in REE patterns between the different deposit types.

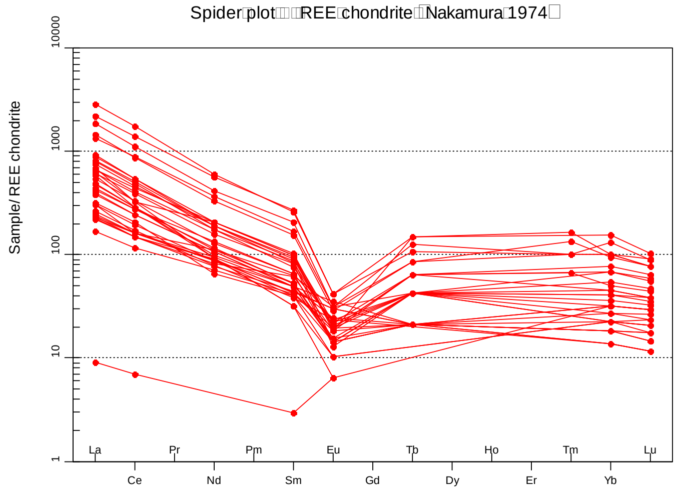


Figure 9. Chondrite-normalized (Nakamura, 1974) REE plots of mineralized veins and breccias from the Cornudas Mountains. Data are from Schreiner (1994).

Table 2. Summary of fluid inclusion and stable isotope data of REE deposits, indicating a magmatic hydrothermal origin with mixing of meteoric waters.

Name	Temperature degrees C	Salinities	Delta D per mil	Delta ^{18}O per mil	Delta ^{34}S per mil	Conclusion	Reference
Capitan	600	84 eq wt% NaCl + KCl	-54 to -80	7.1 to 8		magmatic fluids	Campbell et al. (1995)
Gallinas	400	15 eq wt% NaCl				meteoric fluid, with REE magmatic	Williams-Jones et al. (2000)
Gallinas	200-310			15.0 to 23.8	-21.1 to 1.5, 9.6 to 13.3	hydrothermal	Vance (2013)

Conclusions

Age dating indicates that the Wind Mountain pluton in the Cornudas Mountains is the oldest of the four REE deposits at 36.6 Ma and the Laughlin Peak volcanic complex spans 22.8 to 32.3 Ma (Table 1). Several studies have attributed changes in the chemistry and source of the magmas to the tectonic transition between Eocene-early Oligocene subduction (Laramide, 36-75 Ma) and mid-Tertiary extension (20-36 Ma; Allen and Foord, 1991; McMillan et al. 2000; Anthony, 2005).

The alkaline igneous rocks within the four districts are likely partial melting within the lithosphere mantle and lower crust, possibly reflecting metasomatism of the upper mantle (Mutschler et al., 1987; Kelley and Luddington, 2002; Pilet at al., 2008). Rollback of the Farallon flat slab occurred 23-37 Ma and resulted in tremendous pulse of calc-alkaline ignimbrite eruptions in western New Mexico and central Mexico (Chapin et al., 2004; Chapin, 2012). In eastern New Mexico, the Sierra Blanca alkaline volcanic complex was erupting along with emplacement of smaller, localized subalkaine to alkaline plutons, laccoliths, and sills that form the North American Cordilleran alkaline-igneous belt. As the Farallon slab fragmented (Henry et al., 2010; Chapin, 2012), the asthenosphere filled gaps between the sinking slab and overlying lithosphere, producing magmas. Richards (2009) suggests that alkaline-related gold deposits are formed by remelting of previously subducted arc lithosphere. Magmas of the North American Cordilleran alkaline-igneous belt were emplaced at the edge of this activity, along the tectonic boundary between the Basin and Range province (including the Rio Grande rift) and the cooler thicker crust of the Great Plains (North American interior craton). This tectonic boundary provided resistance to deformation and emplacement of magmas and, allowed for differentiation of magmas to alkaline affinities (McLemore, 1996; Chapin, 2012), thus accounting for the local variations in chemistry and style of intrusions and associated mineralization.

The REE deposits in the Gallinas Mountains are among the highest potential for REE in New Mexico. The chondrite-normalized REE patterns are similar for the different types of deposits within a district as well as between districts, even though different REE minerals are found in the four districts. Isotopic data in the Capitan Mountains and Gallinas Mountains indicate the veins and breccia pipes are magmatic-hydrothermal with mixing of meteoric waters.

Acknowledgments

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