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MINERALOGY AND GEOCHEMISTRY OF SELECTED RARE EARTH ELEMENTS (REE) DEPOSITS IN THE NORTH AMERICAN CORDILLERAN ALKALINE-IGNEOUS BELT IN NEW MEXICO

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ABSTRACT

Present and emerging technologies are renewing interest in domestic rare earth elements (REE) production. REE deposits throughout the North American Cordilleran alkaline-igneous belt are being re-examined for their economic potential. In New Mexico, the mineral deposits found in this belt are associated with Eocene–Oligocene alkaline to calc-alkaline igneous rocks. Four areas in New Mexico have been examined for their REE potential. The chondrite-normalized REE patterns are similar for all four districts, even though different REE minerals are found. Crandallite, xenotime, bastnäsite and brookite are found in fluorite veins and carbonatites at Laughlin Peak. Bastnäsite was extracted during fluorite processing from 1954-1980 from the Gallinas Mountains, where samples as high as 8% total REE are found in fluorite veins. Other REE minerals include agardite, parasite, xenotime, and monazite. Allanite, thorite and as much as 8133 ppm total REE are found in fluorite veins in the Capitan Mountains. In the Cornudas Mountains, exploration along the outer edge of the Wind Mountain nepheline syenite laccolith and within phonolite dikes, plugs, skarns and carbonate-replacement deposits in Chess Draw contain as much as 3110 ppm TREE, hosted in eudialyte, monazite, bastnäsite, and calciocatapleiite.

INTRODUCTION

Lindgren (24) 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. The North American Cordilleran alkaline-igneous belt is a north-south belt of alkaline igneous rocks and crustal thickening that roughly coincides with the border between the Great Plains physiographic margin and the Basin and Range (including the Rio Grande rift) and Rocky Mountains physiographic provinces (42, 43, 5, 68, 56, 26, 18, 19, 33).

In New Mexico, the mineral deposits found in the North American Cordilleran alkaline-igneous belt (Fig. 1) are associated with Eocene-Oligocene alkaline to calc-alkaline rocks that were called Great Plain Margin (GPM) deposits (45, 46, 26, 27). Alternative classifications by other workers include Au-Ag-Te veins (10, 4, 20), alkalic-gold or alkaline-igneous related gold deposits (15, 68, 69, 42, 43, 5, 55, 18), porphyry gold deposits (57, 55), 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. Four Eocene-Oligocene alkaline to calc-alkaline areas in New Mexico have been examined over the last 20 years for their REE potential: Laughlin Peak and Gallinas, Capitan, and Cornudas Mountains. Other districts in the North American Cordilleran alkaline-igneous belt in New Mexico are predominantly gold- and/or molybdenum-bearing districts, with minor or no REE deposits (Fig. 2; 30, 31, 33).

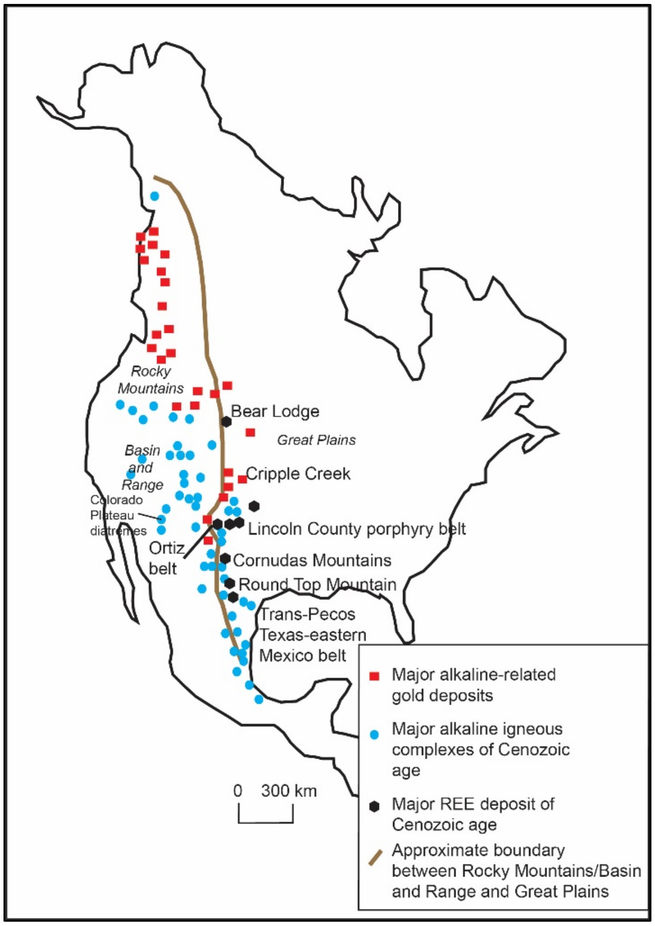


Figure 1. Simplified map showing the extent of the North American Cordilleran alkaline-igneous belt (modified from 43, 33).

Although many geologists have studied these four REE deposits (Table 1, see APPENDIX), no one has compared the geochemistry of the associated igneous rocks and their associated mineral deposits. The purpose of this paper is to compare the geology, geochronology, geochemistry, and mineralogy of the igneous rocks and the REE mineral deposits in these four districts 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 (42, 46, 26, 27, 32, 29, 33) and includes results of new mapping, geochemical, and geochronological studies in the Gallinas and Cornudas Mountains (39, 40) and geochronological studies in the Laughlin Peak area (76).

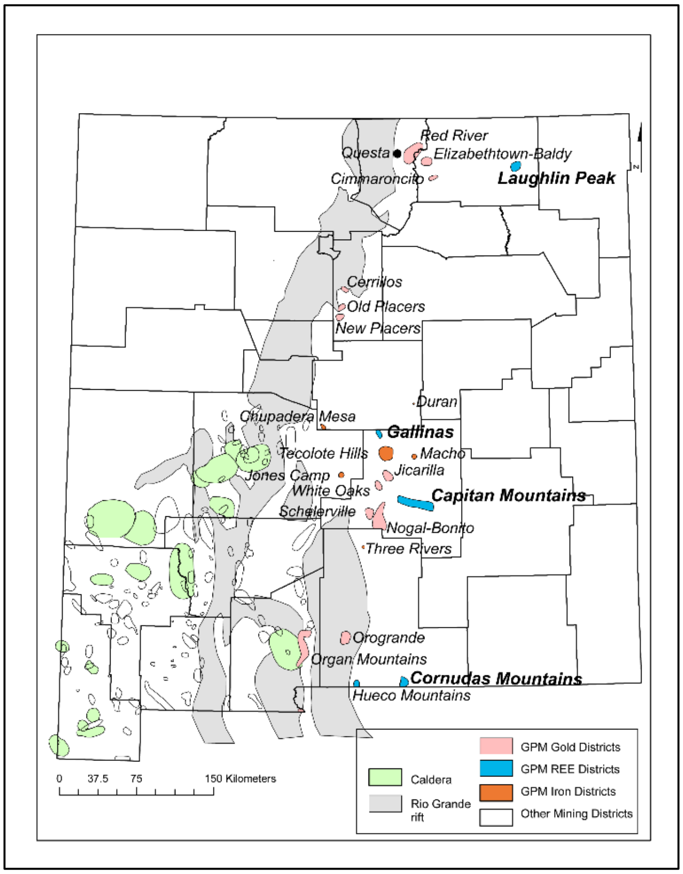


Figure 2. Mining districts related to the North American Cordilleran alkaline-igneous belt (GPM or Great Plains Margin deposits), Rio Grande rift, calderas, and other Eocene-Miocene mining districts in New Mexico (8, 9, 33, 36, 37, 62).

METHODS OF STUDY

Data used in this report have been compiled from a literature review (references cited in Table 1), field examination and mapping, and unpublished geochemical and geochronological data by the authors, 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 are available upon request. The data were plotted on various geochemical and tectonic diagrams (17, 14, 48, 58).

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 both shallow intrusions and deeper plutonic rocks. The nomenclature of intrusive igneous rocks in this report mostly conforms to the International classification (23), 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 (11) and R1-R2 (12) diagrams. Mineralized areas were examined and sampled during 1980-2022 by the authors, and during 1982-1994 by the U.S. Bureau of Mines and U.S. Geological Survey as part of mineral resource assessments (70, 63, 64, 65, 59, 60, 61, 21).

DESCRIPTION OF REE DEPOSITS

REE in igneous intrusions are found in two districts (Table 1); Laughlin Peak (carbonatites) and Cornudas Mountains (nepheline syenite, phonolite). REE in breccia pipes and dikes are found in the Laughlin Peak, Gallinas and Cornudas Mountains. REE in skarns and carbonate-replacement deposits are found in three districts (Gallinas, Capitan, and Cornudas Mountains). REE-vein deposits are found in three districts (Table 1): Laughlin Peak, Gallinas and Capitan Mountains.

The REE minerals are different in each district (Table 1). The REE deposits in these districts are typically structurally controlled. Limited fluid inclusion studies from the Gallinas and Capitan Mountains deposits indicates temperatures of formation of 200-600°C from high salinity fluids, consistent with mixing and cooling of magmatic and meteoric waters, and leaching from host rocks (Table 2, see APPENDIX). The REE deposits are typically not found with significant gold deposits, although trace amounts of gold are locally present (39, 40, 59, 60, 61). Fluorite as a predominate mineral in REE deposits are only significant in the Gallinas Mountains where fluorite was produced, however fluorite is found in small amounts in most GPM districts, including the Laughlin Peak and Capitan and Cornudas Mountains (25; unpublished data by the author).

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 36.6 Ma (Fig. 3) 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 (39, 60).

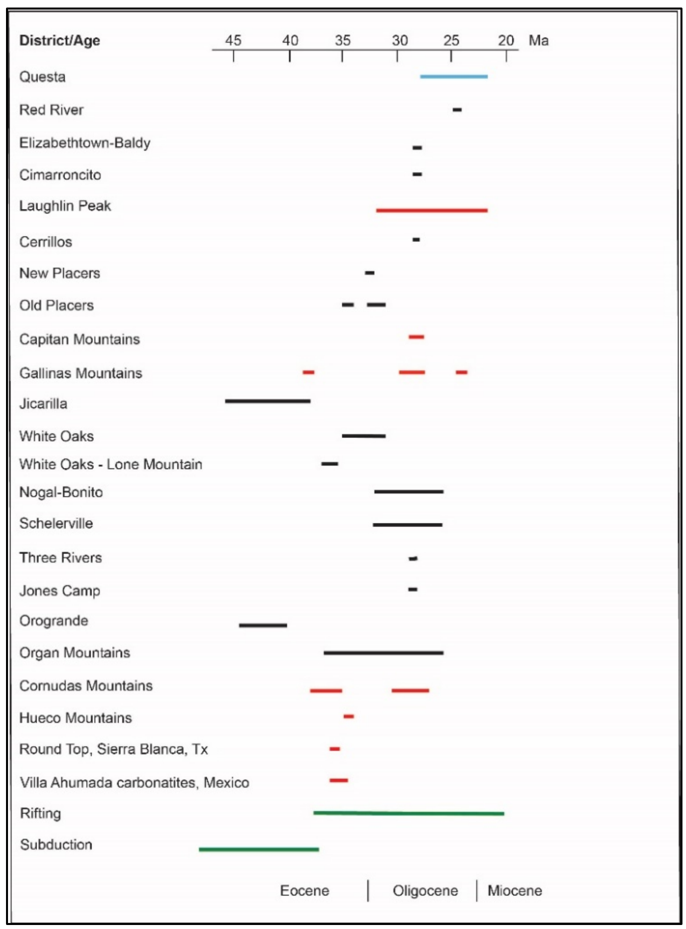


Figure 3. Ages of igneous rocks associated with North American Cordilleran alkaline-igneous belt (i.e. GPM districts) in New Mexico, Texas, and eastern Mexico, arranged from north to south (modified from 33 with new data from 39, 40, 76). The blue line represents predominantly porphyry molybdenum deposits, black lines represent

primary gold and base metals districts, and the red lines represent predominantly REE districts. The green lines represent rifting and subduction (41, 9). Previous $^{40}Ar/^{39}Ar$ ages have been recalculated using the new monitor age 28.201 Ma (22). Locations are in Figure 2.

The igneous rocks in the districts are trachytes, syenites to nepheline syenites, phonolites, and other subalkaline to alkaline rock types. Granites are found in the Capitan Mountains and rhyolites are found in the Gallinas Mountains (Fig. 4, 5, 6, 7). Carbonatites, classified as ferrocarbonatites, are found in the Laughlin Peak area (Fig. 4). The rocks are typically metaluminous to peraluminous intrusions, with light REE-enriched patterns with or without a europium anomaly. Igneous rocks in three of the REE districts (Laughlin Peak, Gallinas and Cornudas Mountains) are ferroan, alkali-calcic to alkali (according to 14). The rhyolite and granites of the Gallinas and Capitan Mountains are similar in chemical composition (Fig. 8, 9), especially in major elements. Geochemically, the rocks from all four districts plot as WPG (within-plate granites) to VAG (volcanic arc granites) (48), and active continental margins (58). Most igneous rocks plot as A-type granitoids except for the Laughlin Peak igneous rocks, which overlap the I/S and A-type granitoids (72). Detailed geologic mapping in these districts have documented evidence of local structural control of intrusive rocks and mineral deposits (63, 64, 65, 38, 39, 40).

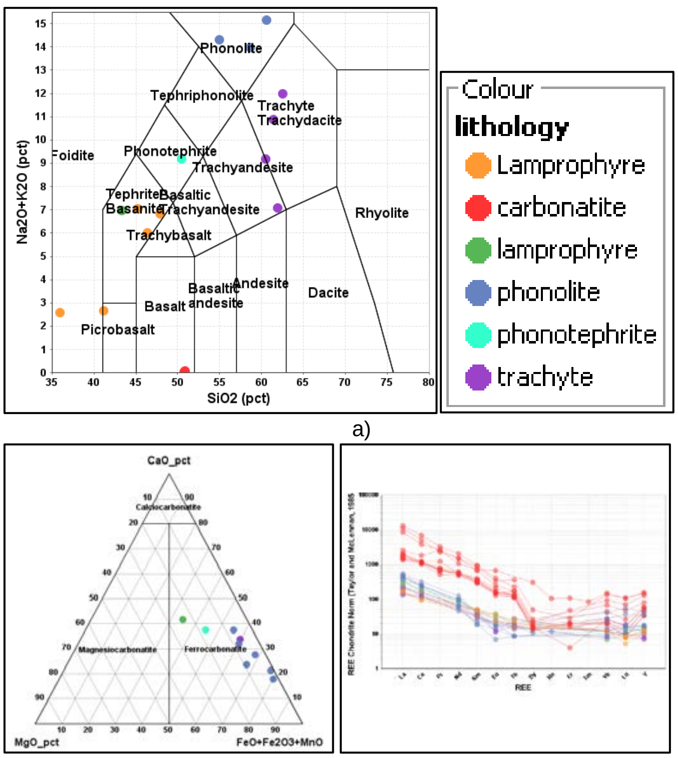


Figure 4. Chemical plots of Laughlin Peak igneous rocks: a) TAS (total alkali vs silica) plot for volcanic rocks (23), b) classification of carbonatites (23), c) REE chondrite-normalized plot (67). Chemical analyses are in 32.

Mineralized veins, skarns (including carbonate-replacement deposits), and breccia pipes and dikes from the four areas typically exhibit higher REE concentrations than the igneous rocks (Fig. 8, 9, 10, 11). Note that the economic targets in the Laughlin Peak area include the carbonatites (Fig. 4) and in the Cornudas Mountains include eudialyte-bearing phonolites and nepheline syenites (Fig. 7). The chondrite-normalized REE patterns are similar for all four districts (Fig. 4, 5, 6, 7), even though different REE minerals are found. Crandallite, xenotime, bastnäsite and brookite are found in fluorite veins and carbonatites at Laughlin Peak (32). Bastnäsite was extracted during fluorite processing from 1954-1980 from the Gallinas Mountains, where samples as high as 8% total REE are found in fluorite-REE veins (39). Other REE minerals include agardite, parasite, xenotime, and monazite. Allanite, thorite and as much as 8133 ppm total REE are found in quartz veins in the Capitan Mountains (33). In the Cornudas Mountains, exploration along the outer edge of the Wind Mountain nepheline syenite laccolith and within dikes and plugs in Chess Draw contain as much as 3110 ppm total REE, hosted in eudialyte, monazite, bastnäsite, and calciocatapleiite in phonolite dikes, nepheline syenite, and adjacent skarns and carbonate-replacement deposits (40).

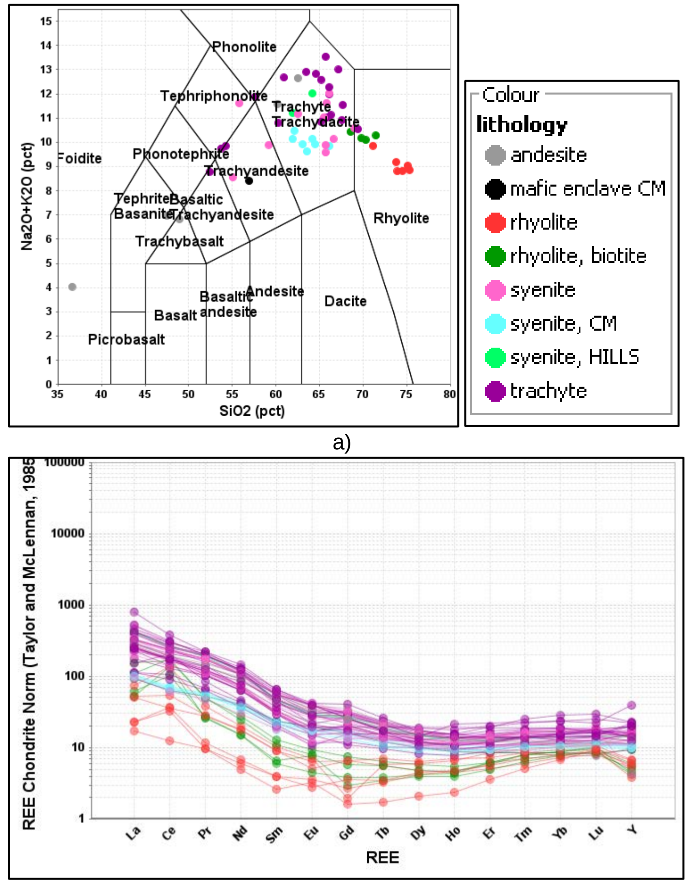


Figure 5. Chemical plots of Gallinas Mountains igneous rocks: a) TAS (total alkali vs silica) plot for volcanic rocks (23), b) REE chondrite-normalized plot (67). Chemical analyses are in 39.

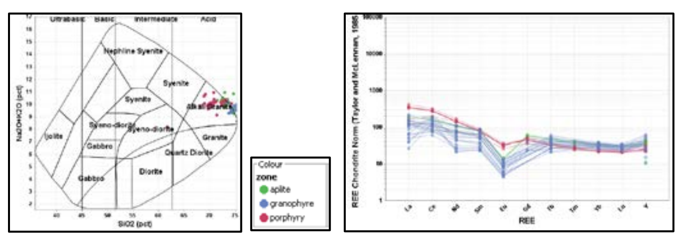
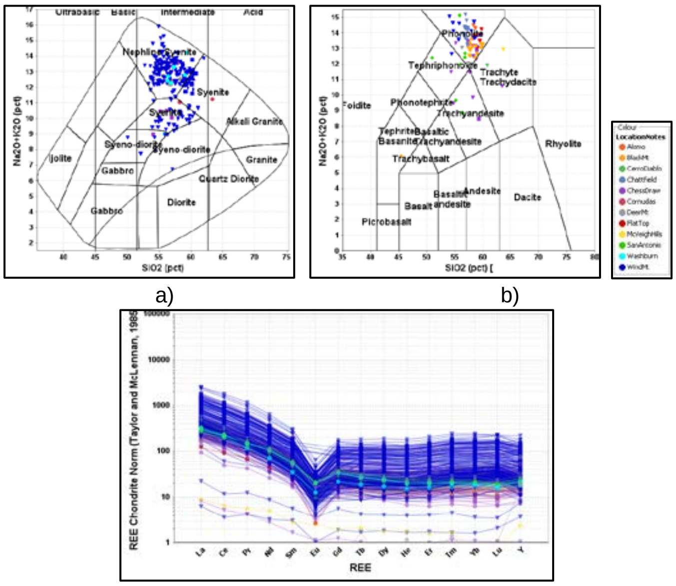


Figure 6. Chemical plots of Capitan Mountains igneous: a) TAS diagram for plutonic rocks (11, 74), b) REE chondrite-normalized plot (67). Chemical analyses are in 33, 34.

DISCUSSION AND CONCLUSIONS

Geochronology studies indicate that the Wind Mountain pluton in the Cornudas Mountains is the oldest of the four REE deposits at 36.6 Ma (40) and the Laughlin Peak district has the youngest igneous rocks at 22.8 Ma (Fig. 4; Table 1). The similar compositions of GPM igneous rocks suggest that the magmas had a similar origin and were produced from similar source regions that did not change much over 14 Ma. Subtle differences in chemical composition 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. 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; 1, 41, 3).



a) b)

c)

Figure 7. Chemical plots of Cornudas Mountains igneous rocks: a) TAS diagram for plutonic rocks (11, 74). The curved line separates the alkaline (above the curve) from subalkaline (below the curve) rocks (17), b) TAS (total alkali vs silica) plot for volcanic rocks (23), c) REE chondrite-normalized plot (67). Chemical analyses are in 40.

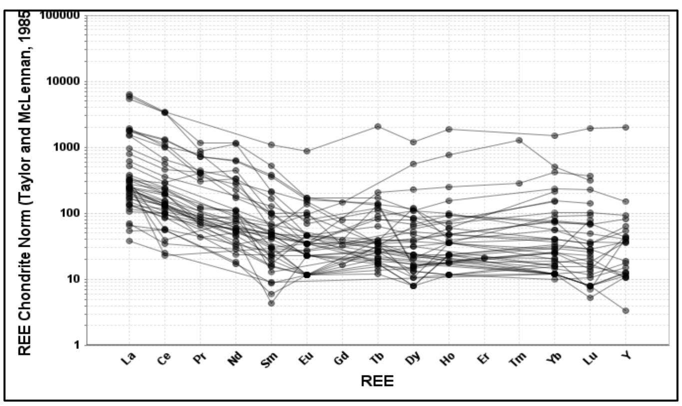


Figure 8. REE chondrite-normalized plot (67) for veins and breccias in the Laughlin Peak area. Chemical analyses are in 32. See Figure 8 for REE chondrite-normalized plot of carbonatites.

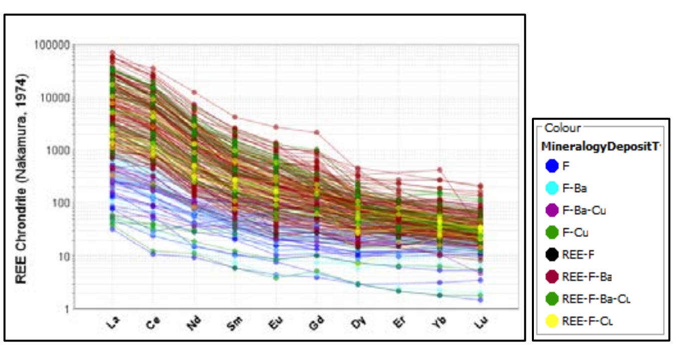


Figure 9. REE chondrite-normalized plot (67) for F-REE hydrothermal breccia and fissure veins in the Gallinas Mountains. Chemical analyses are in 39.

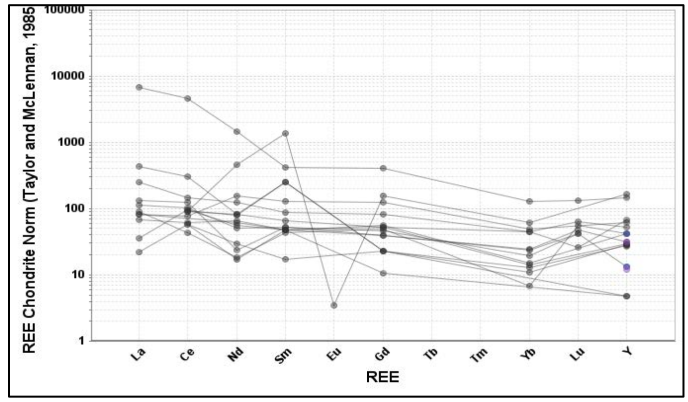


Figure 10. REE chondrite-normalized plot (67) for REE veins in the Capitan Mountains. Chemical analyses are in 33, 34.

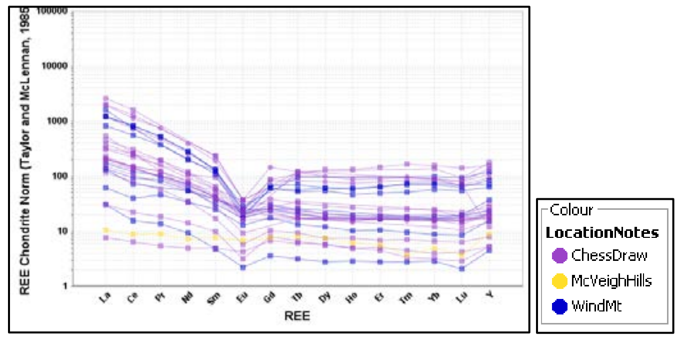


Figure 11. REE chondrite-normalized plot (67) for REE breccias, skarns and carbonate-replacement deposits in the Cornudas Mountains. Chemical analyses are in 40. See Figure 7 for REE chondrite-normalized plot of igneous rocks.

The igneous rocks in three areas have intruded into Permian limestones and other sedimentary rocks (Cornudas, Gallinas, and Capitan Mountains; 34, 39, 40), whereas the Laughlin Peak igneous rocks have intruded into Triassic, Jurassic, and Cretaceous sandstones and shales (63, 64, 65). Skarns and carbonate-replacement deposits are only present in the Cornudas, Gallinas, and Capitan Mountains (Table 1). More quartz is present in the Gallinas and Capitan F-REE veins deposits than most alkaline-related REE deposits as a result of the host quartz sandstones.

The alkaline igneous rocks within the four districts are likely derived from partial melting within the lithosphere mantle and lower crust, possibly reflecting metasomatism of the upper mantle (42, 43, 19, 20, 51). Rollback of the Farallon flat slab occurred 37-23 Ma and resulted in tremendous pulses of calc-alkaline ignimbrite eruptions in western New Mexico and central Mexico (7, 9). In eastern New Mexico, the Sierra Blanca alkaline volcanic complex was erupting along with emplacement of smaller, localized subalkaline to alkaline plutons, laccoliths, and sills that form the North American Cordilleran alkaline-igneous belt. As the Farallon slab fragmented (16, 9), the asthenosphere filled gaps between the sinking slab and overlying lithosphere, producing magmas. Richards (55) suggests that alkaline-related gold deposits could be 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 (7, 33), 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 economic potential for REE in New Mexico; some samples are as high as 8% total REE (39). Some samples in the Cornudas

Mountains contain as much as 3110 ppm total REE; REE could be leached from a mineral concentrate of the REE-bearing minerals from the Cornudas Mountains (eudialyte, zircon, monazite, bastnäsite, calcio-catapleiite, vitusite, xenotime) (40). Drilling is required to delineate potential economic deposits in all four districts. 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 and Gallinas Mountains indicate the veins and breccia pipes are magmatic-hydrothermal with mixing of meteoric waters (Table 2).

RECOMMENDATIONS FOR FUTURE STUDIES

- Additional detailed geochemistry and geochronology is needed in the Capitan Mountains and Laughlin Peak areas.
- Isotopic geochemistry is required to further define the magma sources.

ACKNOWLEDGMENTS

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APPENDIX

Table 1. Summary of four 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 McLemore (2018). Ages in bold italics are by $^{40}Ar/^{39}Ar$ methods, other ages are predominantly by K/Ar methods (see Fig. 3).

District ID	Name of district	Commodities present (produced are in bold)	Age Ma (bold italics are $^{40}Ar/^{39}Ar$)	REE-bearing intrusions	REE-bearing breccia pipes and dikes	REE-bearing skarns and carbonate-hosted deposits	REE-bearing veins	Predominant mineralogy	References
DIS020	Laughlin Peak	REE, Th, U, Au	***32.5-22.8***	x (carbonatite)	x		x	crandallite, xenotime, brookite, quartz, calcite, feldspar, barite, fluorite, rutile, zircon, pyrite, fluorite	63, 64, 65, 66, 88, 59, 76
DIS091	Capitan Mountains	**Fe,** REE, Th, **U**, Be, **quartz crystals**	***28.3***			x (Fe)	x	quartz, fluorite, adularia, calcite, fluorite, titanite, allanite, thorite	33, 34, 50, 54, 2, 6, 13
DIS092	Gallinas Mountains	**Cu, Pb, Zn, Ag, Au, REE**, **Fe**, Th, U, Te	3 pulses, ***29-27, 28.8, 25.8-24.4***		x	x (Fe)	x	fluorite, barite, quartz, pyrite, bastnäsite, calcite, galena, bornite, chalcocite, agardite, parasite, xenotime, monazite	28, 49, 21, 60, 71, 73, 40
DIS128	Cornudas Mountains	REE, Th, U, Be, **nepheline syenite**	2 pulses, ***37.14-34.5, 32.48-26.95***	x (nepheline syenite, phonolite)	x	x		eudialyte, monazite, bastnäsite, calciocatapleiite, calcite	35, 40, 44, 53, 61

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 Mountains	600	84 eq wt% NaCl + KCl	-54 to -80	7.1 to 8		magmatic fluids	6
Gallinas Mountains	400	15 eq wt% NaCl				meteoric fluid, with REE magmatic	73
Gallinas Mountains	200-310			15.0 to 23.8	-21.1 to 1.5, 9.6 to 13.3	hydrothermal	71