New Mexico GEOLOGY

August 2015
Volume 37, Number 3

New Mexico Bureau of Geology and Mineral Resources / A Division of New Mexico Tech

New Mexico GEOLOGY

August 2015
Volume 37, Number 3

Rare Earth Elements (REE) Deposits in New Mexico: Update *Virginia T. Mclemore*...**59**

Gallery of Geology—Bastnäesite, *Virginia T. McLemore*...**69**

William Richard Dickenson (1931–2015) A Personal Farewell, *Timothy F. Lawton*...**70**

Cover Image

The cover image taken by Virginia McLemore shows a Carbonatite dike (brown) intruding Proterozoic diorite in the Lemitar Mountains, Socorro County, New Mexico. The carbonatite has been dated by Ar/Ar methods as 517.7±0.7 Ma. REE are mined from large carbonatite plutons at Mountain Pass, California and Bayan Obo, Inner Mongolia, China.

A publication of
New Mexico Bureau of Geology and Mineral Resources,
a division of New Mexico Institute of Mining and Technology

Science and Service
ISSN 0196-948X

Editors: Gina D'Ambrosio, Richard Arthur

Design, Layout, Production: Gina D'Ambrosio
Cover image: © Virginia McLemore
Cartography & Graphics: Leo Gabaldon, Stephanie Chavez, and Ginger McLemore

EDITORIAL BOARD

Dan Koning, *NMBGMR*
Penelope Boston, *NMIMT*
Barry S. Kues, *UNM*
Jennifer Lindline, *NMHU*
Gary S. Morgan, *NMMNHS*

New Mexico Institute of Mining and Technology
President
Daniel H. López

New Mexico Bureau of Geology and Mineral Resources
Director and State Geologist
Matthew J. Rhoades, CPG, RG

BOARD OF REGENTS

Ex-Officio
Susana Martinez
Governor of New Mexico

Dr. Barbara Damron
Secretary of Higher Education

Appointed
Deborah Peacock
President, 2011–2016, Albuquerque

Jerry A. Armijo
Secretary/Treasurer, 2015–2020, Socorro

David Gonzales
2015–2020, Farmington

Donald Monette
2015–2018, Socorro

Myissa Weiss, *student member*
2015–2016, Farmington

New Mexico Geology is an "electronic only" publication as of 2015. Each issue is available as a free Pdf download from the New Mexico Bureau of Geology and Mineral Resources website. Subscribe to receive e-mail notices when each issue is available at: **geoinfo.nmt.edu/publications/subscribe**

Editorial Matter: Articles submitted for publication should be in the editor's hands a minimum of five (5) months before date of publication (February, May, August, or November) and should be no longer than 20 typewritten, double-spaced pages. All scientific papers will be reviewed by at least two people in the appropriate field of study. Address inquiries to Gina D' Ambrosio, Managing Editor, New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico 87801-4750; phone (575) 835-5218.

Email: nmgeology@nmbg.nmt.edu

Web page: geoinfo.nmt.edu/publications/periodicals/nmg

Rare Earth Elements (REE) Deposits in New Mexico: Update

Virginia T. McLemore, New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro, NM 87801 *ginger@nmbg.nmt.edu*

Abstract

Deposits of rare earth elements (REE) are located in New Mexico, but they have not been important exploration targets in past years because demand has been met elsewhere. However, with a projected increase in demand, New Mexico deposits are being re-examined for their REE potential. REE-Th-U veins are found in the Gallinas, Capitan, and Cornudas Mountains and Laughlin Peak-Chico Hills; all are associated with Tertiary alkaline to alkalic-calcic igneous rocks. A small amount of bastnaesite, a REE mineral, was recovered during processing of fluorite mined in the Gallinas Mountains. Resources in the Gallinas Mountains amount to at least 537,000 short tons of 2.95% total REE. Four types of deposits are found in the Gallinas Mountains: epithermal REE-F veins, Cu-REE-F veins, REE-F breccia pipes and iron skarn deposits. The abundance of REE and other unusual minerals in the Cornudas Mountains suggests that the area has potential for undiscovered deposits of REE, niobium, and zirconium. U.S. Borax sampled and drilled in the Chess Draw area and found up to 0.06% total REE in samples. Other types of REE deposits in New Mexico include carbonatites in the Lemitar and Chupadera Mountains, Laughlin Peak-Chico Hills, Lobo Hill, and Monte Largo (Sandia Mountains). Disseminated Y-Zr deposits in Proterozoic syenite and nepheline syenite are known at Pajarito Mountain on the Mescalero Apache Indian Reservation near Ruidoso, where one sample contained 6,869 ppm total REE. In 1990, Molycorp, Inc. reported historic resources of 2.7 million short tons grading 0.18% $Y2O_3$ and 1.2% ZrO_2 as disseminated eudialyte. The U.S. Bureau of Indian Affairs drilled five holes in 2014 and results are pending. Two additional deposit types have potential for REE in New Mexico: (1) Cretaceous heavy mineral, beach-placer sandstone deposits and (2) pegmatites. Drilling of one of these deposits, the Apache Mesa (formerly the Stinking Lake) beach-placer sandstone deposit in the Jicarilla Indian Reservation is expected to occur in the fall of 2015. Exploration has occurred in the Lemitar, Gallinas, and Cornudas Mountains for hydrothermal vein deposits. Many challenges, including permitting, face these industries in supplying REE elements. Most REE deposits are radioactive, although they contain less uranium and thorium then uranium mines, but will require special handling of the mine waste. Future development of these commodities will be challenging and more research is required to fully understand the REE potential in New Mexico.

Rare Earth Element	Symbol	Oxide	Conversion factor (% element x conversion factor = % oxide)	Atomic Number	Abundance in the upper crust (ppm)
Scandium	Sc	Sc_2O_3	1.5338	21	14
Yttrium	Y	Y_2O_3	1.269	39	21
Lanthanum	La	La_2O_3	1.173	57	31
Cerium	Ce	Ce_2O_3	1.171	58	63
Praseodymium	Pr	Pr_2O_3	1.17	59	7.1
Neodymium	Nd	Nd_2O_3	1.166	60	27
Promethium	Pm	*	*	61	*
Samarium	Sm	Sm_2O_3	1.16	62	4.7
Europium	Eu	Eu_2O_3	1.158	63	1.0
Gadolinium	Gd	Gd_2O_3	1.153	64	4.0
Terbium	Tb	Tb_2O_3	1.151	65	0.7
Dysprosium	Dy	Dy_2O_3	1.148	66	3.9
Holmium	Ho	Ho_2O_3	1.146	67	0.83
Erbium	Er	Er_2O_3	1.143	68	2.3
Thulium	Tm	Tm_2O_3	1.142	69	0.30
Ytterbium	Yb	Yb_2O_3	1.139	70	2.2
Lutetium	Lu	Lu_2O_3	1.137	71	0.31
Thorium	Th	ThO_2	1.138	90	10.5
Zirconium	Zr	ZrO_2	1.351	40	193
Niobium	Nb	Nb_2O_5	1.431	41	12

Table 1—Description of rare earth elements (REE) (from Taylor and McClennan, 1985; Samson and Wood, 2005; Rudnick and Gao, 2005; Castor and Hedrick, 2006; and Hedrick, 2009). * Promethium does not occur naturally.

Introduction

Overview

Before 2010 most Americans never heard of rare earth elements (REE), except maybe in high school chemistry class when studying the periodic table of elements (Table 1). However, in April 2010, China announced that it would impose immediate export quotas on REE in order to address environmental issues at their REE mines, regulate illegal REE mining operations, and to provide for a sustainable REE production and supply for China (i.e., monopoly, Gambogi and Cordier 2010). This announcement triggered an increase in price for REE and some panic buying. Then, in late September 2010, China halted exports of REE to Japan; the Japanese industry is a significant consumer of REE, particularly for production of electric/hybrid automobiles and

REE oxide	2009 US$/kg[1]	2014 US$/kg[1]	Selected Uses
La oxide	30	5	Fluid cracking catalysts, metallurgy, battery alloys
Ce oxide	30	4–5	Automotive catalysts, metallurgy, polishing powders, glass additives
Nd oxide	42	56–60	Magnets, metallurgy, automotive catalysts
Pr oxide	38	na	Magnets, metallurgy, automotive catalysts
Sm oxide	130	na	Magnets, metallurgy, catalysts
Dy oxide	170	320–360	Magnets, lasers
Eu oxide	1600	680–730	Phosphors, neutron absorber
Gd oxide	150	na	Magnets, phosphores, microwave devices, superconductors
Y oxide	44	15–17	Phosphors, glass additives, ceramics, lasers
Tb oxide	900	590–640	Phosphors, magnets, fuel cells
Er oxide	100	175	Fiber-optic telecommunication cables
Lu oxide	1800	na	Phosphors, catalysts, bubble memory devices
Sc oxide	na	134–221	Metallurgy, metal halide lamps

Table 2—Prices and selected uses of REE. There is significant variation in the price of REE oxides, which are dependent upon purity and product specifications. REE prices are based upon 99% purity in US$/kg. 1—from Cordier (2011) and USGS (2015). na—not available.

consumer electronics (Table 2). Although China reinstated REE exports to Japan in early November 2010 and has since dropped their export quotas, these incidents placed the phrase "rare earth elements" in recent headlines and resource planners, politicians, investors, and journalists throughout the world began to examine the future supply of REE. Today, China has lowered the prices of REE and there is very little active exploration outside of China. The deposits being mined and developed outside of China are struggling due to low REE prices and low investment funding. However, since REE are required for many green energy technologies, the industry will recover in the future and eventually new mines will be needed to meet this demand.

Rare earth elements (REE) include the 15 lanthanide elements (atomic number 57-71), yttrium (Y, atomic number 39), and scandium (Sc, atomic number 21; Table 1) and are commonly divided into two chemical groups, the light REE (La through Eu) and the heavy REE (Gd through Lu, Sc, and Y). REE are lithophile elements (elements enriched in the crust) that have similar physical and chemical properties, and, therefore, occur together in nature. However, REE are not always concentrated into deposits that are economical to mine 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, although not as radioactive as uranium mines.

REE have many specialized applications in industry (Table 2), and for many applications there is no known substitute (Naumov 2008; Hedrick 2009). The U.S. once produced enough REE for U.S. consumption, but since 1999 more than 90% of the REE required by U.S. industry have been imported from China (Haxel et al. 2002). However, the projected increase in demand for REE in China, India, U.S., and other countries has resulted in increased exploration and ultimate production from deposits in the U.S. and elsewhere.

REE deposits have been reported from numerous areas in New Mexico (Fig. 1), but were not considered important exploration targets because demand in past years has been met by other deposits in the world. However, with the projected increase in demand, these areas in New Mexico are being re-examined for their REE potential. The purposes of this report are to (1) summarize the resource potential for REE in New Mexico, (2) update earlier compilations by McLemore et al. (1988a, b), Adams (1965), Long et al. (2010), and McLemore (2014a, 2015a), and (3) suggest areas in the state for future exploration.

For the purposes of this report, a REE occurrence is defined as (1) past production of REE minerals, (2) whole-rock chemical analysis of greater than 1,000 ppm total REE, 500 ppm Y, or 100 ppm Sc, or (3) REE minerals found in sufficient quantities to be considered a potential mineral resource. This is a summary of a larger, more extensive report in preparation. Data used in this report have been compiled from a literature review, field examination, and unpublished data by the author.

District Number	Name	Production	Reference
DIS092	Gallinas Mountains	146,000 lbs of bastnaesite concentrate from fluorite production from veins	Griswold (1959), Adams (1965), McLemore (2010a)
DIS148	Petaca district	112 lbs of samarskite, few hundred lbs of monazite, 12,000 lbs of Ta-Nb-REE ore from pegmatites	Bingler (1968), Jahns (1946)
DIS162	Elk Mountain-Spring Mountain	500 lbs of Ta-U-REE concentrate from pegmatites	Jahns (1946), Holmquist (1946)
DIS164	Rociada	Several thousand tons of REE-Ta ore from pegmatites	Sheffer and Goldsmith (1969), Jahns (1953)
DIS166	Tecolote	$10,000 worth of beryl, tantalite-columbite and monazite from pegmatites	Redmon (1961)
DIS058	Gold Hill	Production in 1950s from pegmatites	Gillerman (1964)

Table 3—REE production from New Mexico deposits.

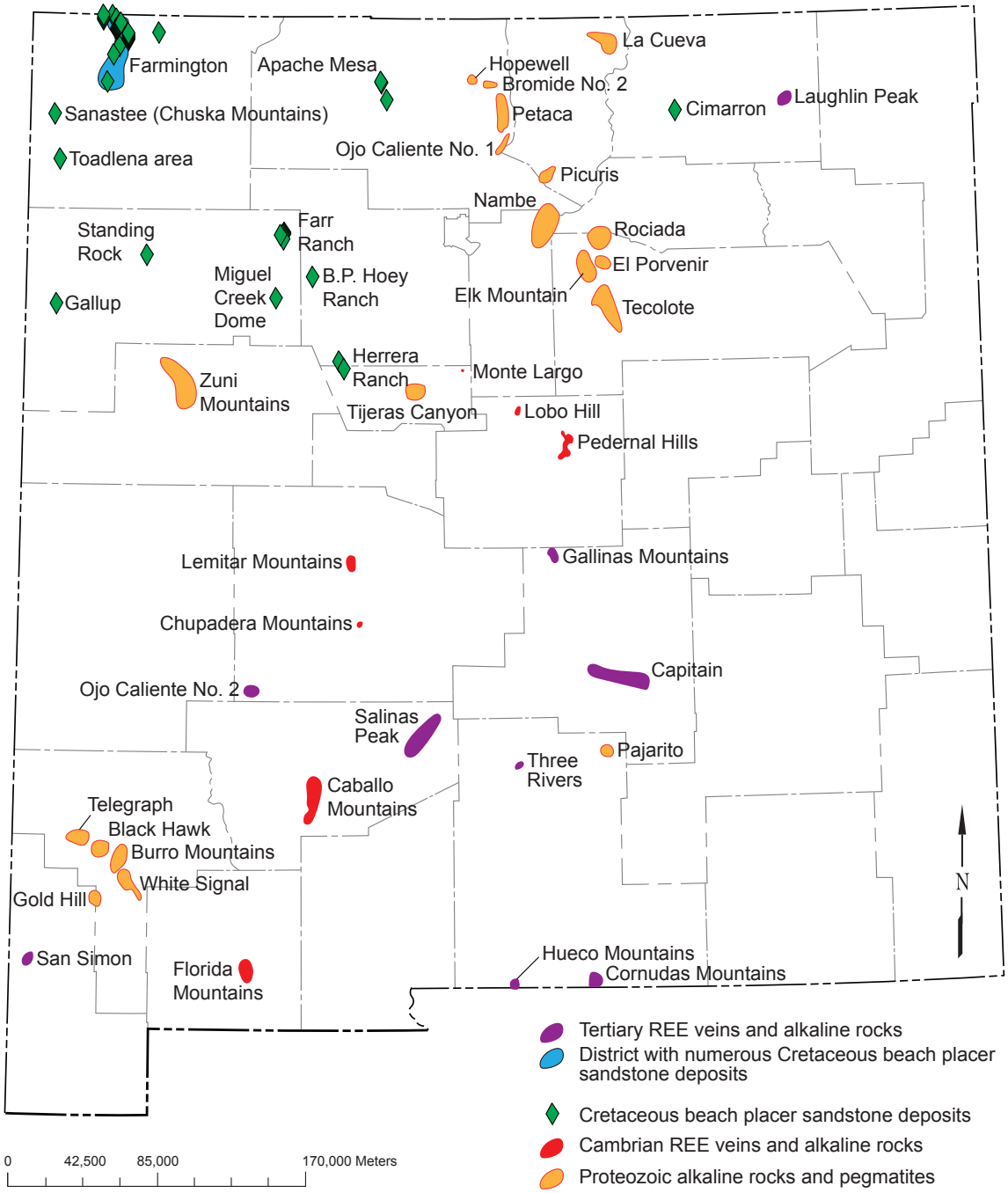


Figure 1—Mining districts in New Mexico that contain rare earth elements (REE) deposits (modified from McLemore et al., 2005a, b; McLemore, 2011, 2014a). Summary of districts is in McLemore (2014a).

Mining and Exploration of REE in New Mexico

REE are found throughout New Mexico and exploration has recently occurred in the Lemitar, Gallinas, and Cornudas Mountains (Fig. 1). The Bureau of Indian Affairs drilled five holes in the Pajarito Mountain Y-Zr deposit on the Mescalero Apache Indian Reservation near Ruidoso in 2014. The NMBGMR has recently investigated REE deposits in veins and breccia pipes in the Gallinas Mountains, episyenites in the Caballo, Burro, and Zuni Mountains, and Cretaceous beach placer sandstone deposits in the San Juan Basin. New Mexico mines produced small amounts of REE as early as the 1940s from some pegmatite deposits in San Miguel, Santa Fe, Rio Arriba, and Taos Counties in northern New Mexico in Grant County in southwestern New Mexico and from the Gallinas Mountains in Lincoln County vein deposits (Table 3).

Types of REE deposits in New Mexico

Alkaline igneous rocks

Many alkaline igneous rocks, typically of syenite or granite composition, have higher concentrations of REE then other types of igneous rocks. Alkaline rocks are defined as rocks with $Na_2O+K_2O>0.3718(SiO_2)-14.5$ (MacDonald and Katsura 1964) or rocks with mol Na_2O+mol K_2O>mol Al_2O_3 (Shand 1951). Peralkaline rocks are particularly enriched in heavy REE, Y, and Zr. Some alkaline igneous rocks in the world contain potential economic REE deposits, and REE, Zr, Be, Nb, Ta, and other elements reside in accessory minerals that are disseminated in the alkaline igneous rock, which can be difficult to separate and process.

Disseminated Y-Zr deposits in syenite are found at Pajarito Mountain (Fig. 1). Several varieties of syenite, nepheline syenite,

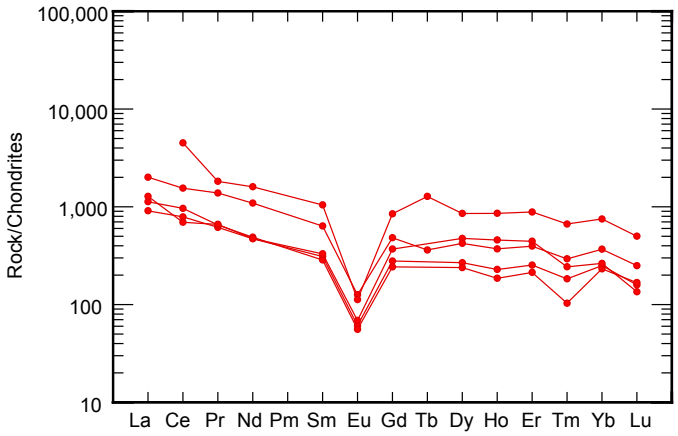


Figure 2— REE chondrite-normalized plot of syenite samples from the Pajarito Mountain deposit, Otero County. Note the enriched light REE pattern. Unpublished chemical analyses are by the author. These plots are used by convention to compare REE analyses. The y-axis shows the ratio of concentration of the element in the sample divided by the concentration of the element in chondrite, using the chondrite values from Nakamura (1974). The x-axis is the element of interest. *Nakamura 1974–REEs.*

quartz syenite, alkali granite, and gabbro are exposed at Pajarito Mountain and are intruded by pegmatite and gabbroic dikes (Kelley 1968; Moore et al. 1988; Sherer 1990; McLemore 1990, 1991). The origin of the Parajito Mountain complex is speculative at present, due to the lack of detailed petrographic and geochemical studies. The mineralogy of the alkaline rocks is complex, consisting of various amounts of essential K-feldspar, plagioclase, arfvedsonite and accessory riebeckite, quartz, eudialtye, fluorite, monazite, apatite, biotite, rutile(?), titanite, aegirine-augite, ziconium silicates, lanthanide and yttrium minerals and zircon. Selected unpublished chemical analyses by the author indicate these alkaline Proterozoic rocks are anonymously high in light-REE (La as high as 1,500 ppm, Ce as high as 3,910 ppm, 6,869 ppm total REE; Fig. 2) and niobium (200 ppm). In 1990, Molycorp, Inc. reported historic resources of 2.7 million short tons grading 0.18% Y_2O_3 and 1.2% ZrO_2 as disseminated eudialyte. Additional feasible studies are required to confirm this historic resource.

Figure 3— View looking southwest across Caballo Lake showing REE-bearing fine-grained episyenite (foreground) in the Northern Caballo granite in the Caballo Mountains.

Other areas in New Mexico have potential for REE associated with alkaline rocks, especially Cambrian-Ordovician episyenites in the Caballo, Burro, and Zuni Mountains (Riggins 2014; Riggins et al. 2014). The term *episyenite* is used to describe altered rocks that were desilicated and metasomatized by alkali-rich fluids (Leroy1978; Recio et al.1997). These metasomatic rocks in the Caballo, Burro, and Zuni Mountains were erroneously called syenites and alkali granites, but are actually metasomatic in origin and not primary igneous rocks. Episyenites are similar to rocks formed by fenitization and are 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 these rocks in the Caballo, Burro, and Zuni Mountains because a carbonatite or alkaline magma source has not been observed at the surface in these areas. Episyenites also are found at Lobo Hill where episyenites, carbonatites, and lamprophyres have been mapped and sampled (McLemore et al. 1999).

The Cambrian-Ordovician alkaline magmatic event is well-documented in southern Colorado and New Mexico and is characterized by carbonatites, episyenites, lamprophyres, and other alkaline rocks dated between 664 and 450 Ma (McLemore et al. 1999; McMillan and McLemore 2004). REE disseminations in episyenites in the Caballo, Burro, Zuni Mountains, Lobo and Pedernal Hills are associated with this Cambrian-Ordovician magmatic event. The episyenites, which are nonfoliated, non-metamorphosed igneous rocks, cross cut Proterozoic foliations and are enriched in REE, U, Th, Nb, and other elements.

McLemore (1986), McLemore et al. (1988a, b, 2012), Riggins (2014), and Riggins et al. (2014) briefly described the known REE-Th-U and Nb episyenite deposits in the Red Hills, Palomas Gap, Longbottom Canyon, and Apache Gap areas of the Caballo Mountains. The episyenites are spotty, discontinuous tabular

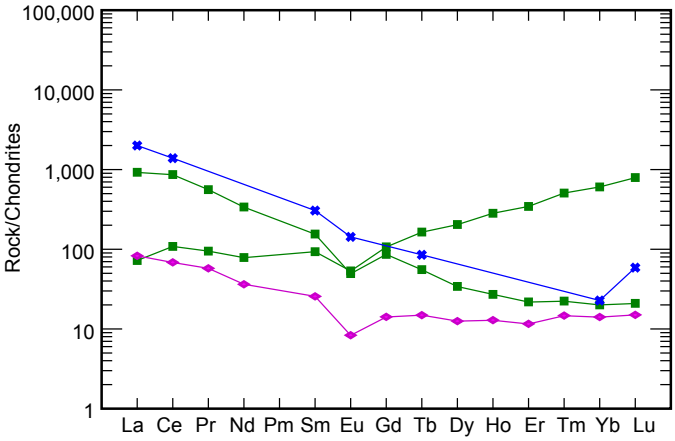


Figure 4— Chondrite-normalized REE patterns (Nakamura, 1974) of selected episyenite samples (green) show enrichments in total REE compared to the host granite (pink) and Lemitar carbonatites (blue). Some episyenites are enriched in HREE, whereas others are enriched in LREE. Most episyenites fall between the LREE and HREE enriched end members. The overall pattern of LREE enrichment is very similar to New Mexico Cambrian–Ordovician carbonatites (blue), (Riggins, 2014). *Nakamura 1974–REEs.*

bodies, narrow lenses, and breccia zones along faults, fractures, and shear zones in Proterozoic rocks (Fig. 3). Selected samples of episyenites from the Red Hills area in the Caballo Mountains contain as much as 20,000 ppm Th, 1,600 ppm U, 500 ppm Nb, 5,000 ppm Y, 600 ppm Be, 7,500 ppm Ga, and 200 ppm La. Some episyenites are enriched in heavy REE (Fig. 4).

Carbonatites

Carbonatites are carbonate-rich rocks of apparent magmatic derivation containing more than 50% magmatic carbonate minerals and less than 20% SiO_2 (Woolley and Kempe 1989; LeMaitre 1989, 2002; Verplanck et al. 2014), and typically are found in zoned complexes consisting of alkaline igneous

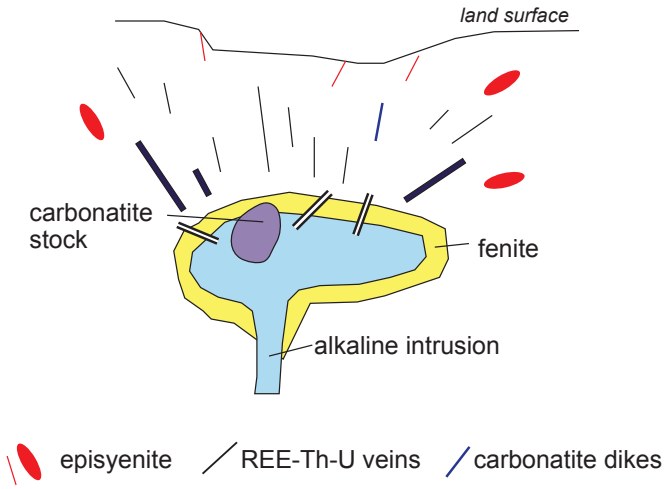


Figure 5—Relationship of Th-REE veins to alkaline rocks and carbonatites. *Modified from Staatz, 2000.*

and/or carbonatite stocks, ring dikes, and cone sheets (Fig. 5). Carbonatites generally contain REE, U, Th, Nb, Ta, Zr, Hf, Fe, Ti, V, Cu, Sr, and are composed of calcite, dolomite, apatite, magnetite, vermiculite, and barite (Singer 2000). Typically, carbonatites are found in continental shields and continental rift environments. Fenitization is the predominant alteration associated with carbonatites; fenites are the altered rocks produced by fenitization. The Mountain Pass carbonatite is the largest economic carbonatite in North America, where bastnaesite was produced from 1954 to 2002 and in 2012 to present. Current

Figure 6—Carbonatite dike (brown) intruding the Proterozoic diorite in the Lemitar Mountains.

reserves at Mountain Pass are estimated at more than 20 million metric tons of ore grading 8.9% total REE oxide (Castor 2008).

Carbonatites localities in New Mexico include the Lemitar and Chupadera Mountains, Laughlin Peak-Chico Hills, Lobo Hill, and Monte Largo (Sandia Mountains) in New Mexico (Fig. 1). Although carbonatites have not been found in the Gallinas Mountains, they are suspected to occur in the subsurface based on mineralogy and alteration (McLemore 2010a). Compositionally, the carbonatites in New Mexico are sövites, rauhaugites, and silicocarbonatites. The dikes are typically 1–5 ft wide (Fig. 6) and up to 1,500 ft long, and contain anonymously high concentrations of REE (Fig. 7), U, Th, and Nb.

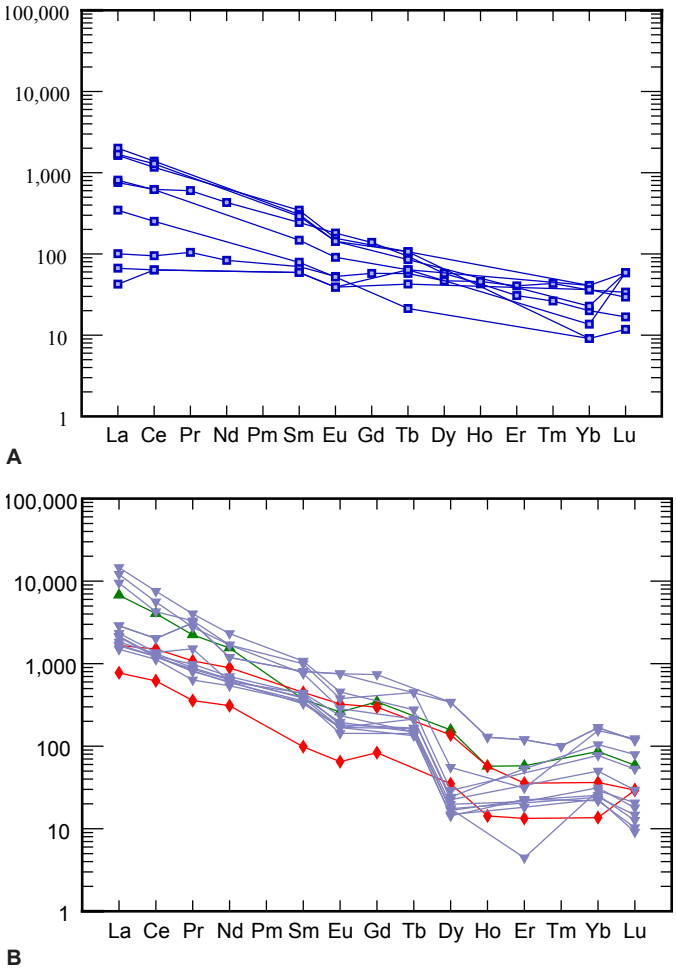


Figure 7—Chondrite-normalized REE patterns for carbonatites in New Mexico. A) Lemitar carbonatites. B) Carbonatites from Chupadera Mountains (red), Lobo Hill (green), and Laughlin Peak districts. *Nakamura 1974–REEs.*

REE-Th-U hydrothermal veins

REE-Th-U hydrothermal vein and breccia deposits (Staatz 2000) consist of various Th and REE minerals and are commonly associated with alkaline igneous rocks and carbonatites. REE-Th-U veins are associated with Tertiary alkaline igneous rocks in New Mexico in the Gallinas, Capitan, and Cornudas Mountains and Laughlin Peak-Chico Hills (Fig. 1). REE-Th-U vein and breccia deposits in New Mexico are typically found as tabular bodies, narrow lenses, and breccia zones along faults, fractures and shear zones. They are a few feet to 1,000s of feet long, as much as 10 ft wide, and can be discontinuous along strike, with varying grades and mineralogy. Globally, REE-Th-U veins are typically associated with carbonatites and alkaline rocks (Fig. 5).

Past production of bastnaesite has come from the Gallinas Mountains (Table 3). Four types of deposits characterize the Gallinas Mountains: epithermal REE-F veins, Cu-REE-F veins, REE-F breccia pipes and iron skarn deposits (McLemore, 2010a). District zonation is defined by Cu-REE-F (±Pb, Zn, Ag) hydrothermal veins that form the center of the district, surrounded by REE-F hydrothermal veins (McLemore 2010a). The magmatic-hydrothermal breccia pipe deposits form a belt partially surrounding the veins and contain the highest gold values, as much as 1,707 ppb (0.05 oz/short ton) Au as reported by Schreiner (1993) and McLemore (2010a). Iron skarns formed at the top and edge of the trachyte/syenite body and are likely the earliest stage of mineralization. The iron skarns are probably related to the REE-F and REE-F-Cu veins and breccias because they typically contain bastnaesite and fluorite and are similar in

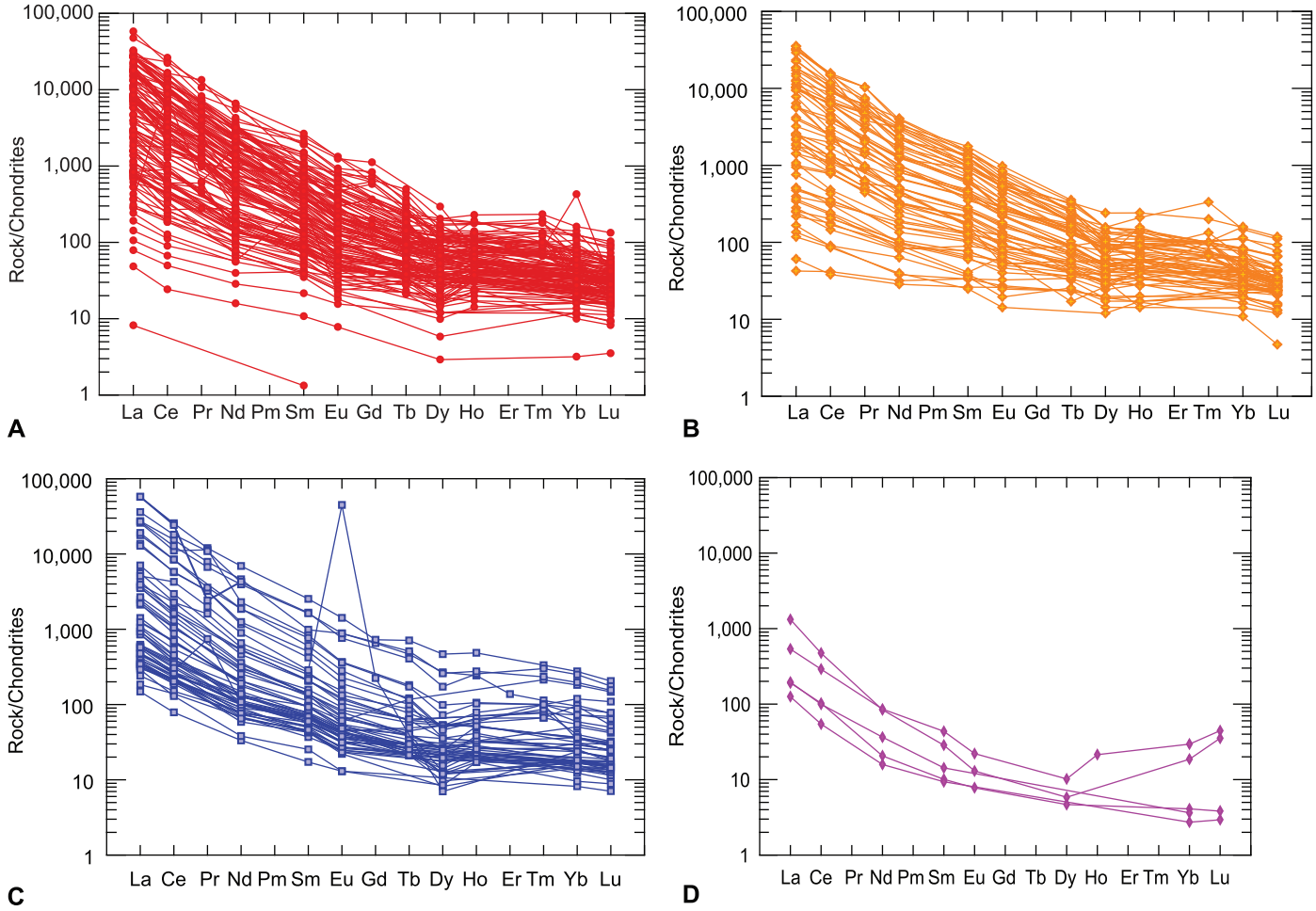


Figure 8—Chondrite-normalized REE plots (Nakamura, 1974) of mineralized samples from the Gallinas Mountains. Data from Schreiner (1993) and McLemore (2010a). Note the similarity in REE patterns between the different deposit types. A) REE-F veins (131 samples); B) Cu-REE-F veins (65 samples); C) Breccia pipe deposits (58 samples); D) iron skarns (6 samples). *Nakamura 1974–REEs.*

REE and other trace element geochemistry (Fig. 8; McLemore 2010a). Fenites exhibit light REE enriched chondrite-normalized REE patterns (Schreiner, 1993). The mineralogy in the Gallinas Mountains is diverse and includes fluorite, quartz, barite, pyrite, iron oxides and accessory bastnaesite, calcite, chalcedony, galena, bornite, chalcocite, pyromorphite, anglesite, chrysocolla, malachite, and azurite and rare agardite (yttrium-arsenic oxide), mimetite, wulfenite, vanadinite, mottramite, cerusite, among others (Perhac 1970; DeMark 1980; DeMark and Hlava 1993; McLemore 2010a; Vance 2013). Resources in the Gallinas Mountains amount to at least 537,000 short tons of 2.95% total REE (not NI-43-101 compliant; Schreiner 1993). A genetic model is summarized by intrusion/extrusion of crustal-derived igneous source rock in an extensional terrain possibly related to an alkaline-carbonatite complex with mineralization related to mixing of magmatic-hydrothermal and formation fluids (Vance, 2013).

Although there has been no mineral production from the Laughlin Peak district, three types of mineral deposits have been identified: (1) carbonatites, (2) breccia pipes, and (3) Th-REE hydrothermal veins (McLemore 2015a, b). Radioactive carbonatite dikes have the chemical composition of predominantly ferruginous calciocarbonatite, with some calciocarbonatite (also known as calcite carbonatite or sövite) and magnesiocarbonatite (also known as dolomite carbonatite or beforsite) and contain <1.6% total REE (Fig. 7, 9). The radioactive Th-REE veins cut Cretaceous sedimentary rocks and Tertiary volcanic flows, dikes and sills, strike predominantly west to northwest with steep north or south dips, and are less than 900 ft long and less than 3 ft wide. Crandallite, xenotime, thorite, and brookite are the predominant REE minerals and contain <1.2% total REE (Fig. 9) and <165 ppb Au. The radioactive intrusive breccia pipes consist of various iron and manganese oxide-stained, angular to subrounded rock fragments in a fine-grained siliceous and carbonate matrix of quartz and feldspar. The total REE is less than 3,017 ppm. The breccia pipes also contain as much as 5,900 ppm F, 9,050 ppm Ba, 535 ppm Nb, 54 ppm U and 82 ppb Au.

The Capitan pluton is associated with Th-REE (±Au, U) vein (Fig. 10), iron skarn and vein, and manganese vein and replacement deposits (McLemore 2014b). Iron and a small shipment of uranium ore were produced from the district. The Th-REE (±Au, U) veins occur along the western end of the pluton. One sample from the McCory prospect contains 8,133 ppm total REE (V.T. McLemore, unpublished data). Iron skarn and vein deposits are found along the western and northeastern portions of the pluton, whereas manganese deposits are along the northeastern portion of the pluton. The Th-REE (±Au, U) veins contain quartz, fluorite, adularia, hematite, calcite, fluorite, titanite, allanite, thorite, chlorite, and clay minerals (McLemore and Phillips 1991). They probably formed from late magmatic fluids evolved from the Capitan pluton as indicated by highly saline (as much as 80% eq. NaCl) fluid inclusions with homogenization temperatures of 500–600°C (Campbell et al. 1995).

The abundant REE and other unusual minerals in the Cornudas Mountains suggests that the area has potential for undiscovered deposits of REE, niobium, and zirconium (Schreiner 1994). U.S. Borax sampled and drilled in the Chess Draw area and reported up to 0.06% total rare-earth oxides,

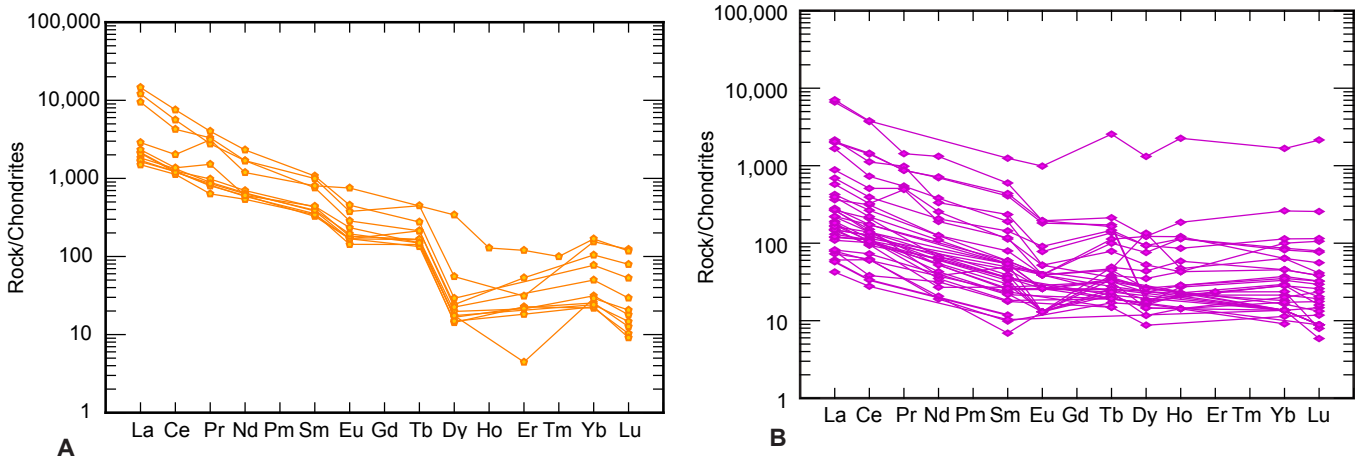


Figure 9—Chondrite-normalized (*Nakamura, 1974*) REE plots of carbonatites. A) and veins; B) from the Laughlin Peak district. Data are from Schreiner (1991) and McLemore (2015b). Nakamura, 1974–REEs.

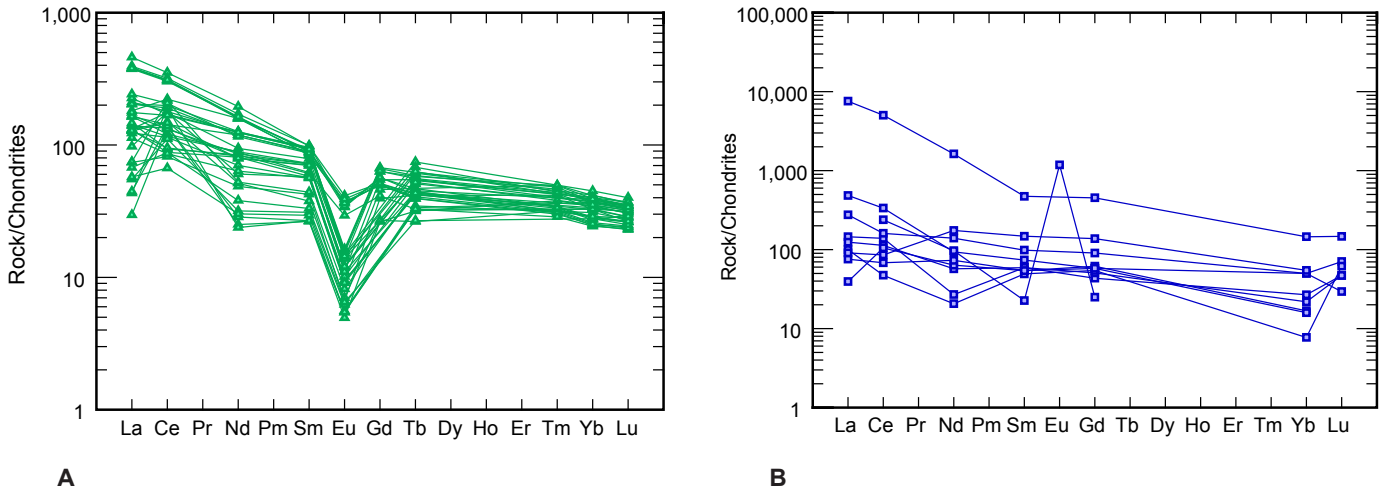


Figure 10—REE plots of granitic rocks (green) A) above left; and REE-Th-U veins (blue) B) above right; in the Capitan Mountains, Lincoln County. Eu was not analyzed in some vein samples. Chondrite values from Nakamura (1974). Data from Alan and McLemore (1991) and V.T. McLemore (unpublished data). *Nakamura, 1974–REEs.*

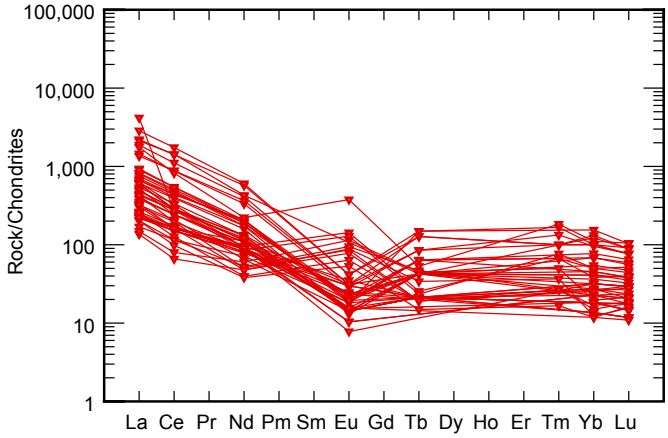


Figure 11—Chondrite-normalized REE plots of mineralized veins and breccias from the Cornudas Mountains. Data are from Schreiner (1994) and unpublished data by the author. *Nakamura, 1974–REEs.*

10–1,400 ppm Nb, 10–3,000 ppm Zr, 230–13,000 ppm F. An analysis of a dike reported by McLemore et al. (1988a, b) contained 1,235 ppm Ce, 700 ppm La, 270 ppm Nd, and 242 ppm Y (Fig. 11). Analyses reported by Schreiner (1994) include as much as 3,790 ppm total REE (Fig. 11), 2,332 ppm Nb, 92 ppm Be, and 3,137 ppm F. Geovic Mining Corp. drilled in the Cornudas Mountains area in 2012, but results are unknown. Additional geologic, geochemical, and other exploration techniques are required to properly evaluate this area, especially in dikes and along intrusive contacts with the limestones.

Pegmatites

Pegmatites are coarse-grained igneous rocks, lenses, or veins with granitic composition, contain essential quartz and feldspar, and represent the last and most hydrous phase of crystallizing magmas (Page and Page 2000; Ercit 2005). Complex pegmatites include mineralogical and/or textural zoning. Pegmatites can contain a variety of economic minerals, including, mica, quartz, feldspar, and are enriched in 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 3), but in general pegmatites in New Mexico are poor mining targets, because the REE minerals are widely dispersed within throughout the pegmatite and are difficult to selectively mine and process.

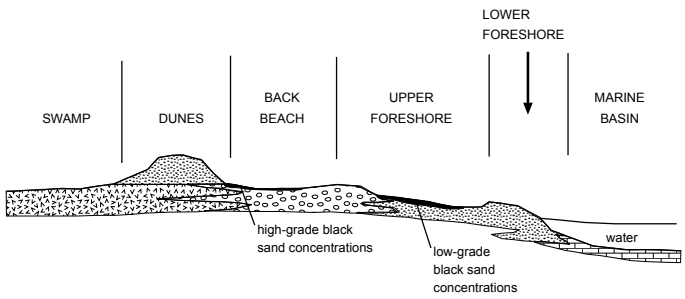


Figure 12—Idealized cross-section of formation of beach placer sandstone deposits (Houston and Murphy, 1970).

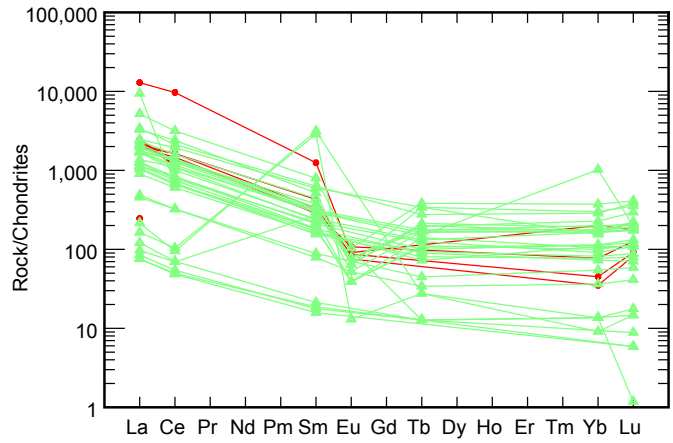


Figure 13—Chondrite-normalized REE plot of selected beach-placer deposits, San Juan Basin, New Mexico. Green are from the Ute Reservation (Zech et al., 1994) and red are from other beach placer deposits (McLemore, 2010b). *Nakamura, 1974–REEs.*

Placer deposits

Placer deposits form by mechanical concentration of heavy minerals in a sedimentary environment, such as a river or beach. Ilmenite, rutile, magnetite, zircon, monazite and xenotime are the predominant economic minerals. Modern examples are Eneabba, western Austalia and Odisha, India. Heavy mineral, beach-placer sandstone deposits is a specific type of placer deposit in New Mexico that contains REE. Heavy mineral, beach-placer sandstone deposits are concentrations of heavy minerals that formed on beaches or in longshore bars in a marginal-marine environment (Fig. 12; Houston and Murphy, 1970, 1977; McLemore, 2010b). Many beach-placer sandstone deposits contain high concentrations of Th, REEs (Fig. 13), Zr, Ti, U, Nb, Ta, and Fe. Detrital heavy minerals comprise approximately 50–60% of the sandstones and typically consist of titanite, zircon, magnetite, ilmenite, monazite, apatite, and allanite, among others. In New Mexico, these deposits are in Cretaceous sedimentary rocks (McLemore, 2010b). The Sanostee deposit is the largest known beach placer sandstone deposit in New Mexico (Fig. 14), but additional sampling and drilling are required to fully delineate the deposit and evaluate the REE resource potential (McLemore 2010b). Drilling of one of these deposits, the Apache Mesa (formerly known as Stinking Lake) deposit in the Jicarilla Indian Reservation, is expected to occur in the fall of 2015.

Another type of placer deposit in New Mexico are placer alluvial deposits formed down slope of REE-enriched Proterozoic pegmatites and granites. Residual placer deposits are reported from Ojo Caliente district in Rio Arriba County, where REE minerals are found in the alluvial sediments derived from pegmatites (Fig. 1).

Figure 14— Beach placer sandstone deposits forming top of cliffs at the Sanostee deposit.

Other potential REE-bearing deposits

Minor amounts of REE can be found in U, Th, and phosphate deposits and, if mined, REE could be recovered as a by-product (Jackson and Christiansen, 1993). Other placer deposits (fluvial, alluvial placers) could carry anomalous amounts of REE. Fluorite veins can carry high concentrations of REE, especially Y. Some Proterozoic granites in New Mexico could have pegmatitic zones that are enriched in REE. Tertiary alkaline igneous rocks associated with gold veins east of the Rio Grande rift are being examined for potential REE deposits (McLemore 2015a). REE also can be associated with uraninite and other U-bearing minerals (Förster 1999; Göb et al. 2013) suggesting that sandstone uranium deposits should be examined for their REE potential, especially as a potential by-product of future uranium production. REE were produced from uraninite at the Elliott Lake paleoplacer U-REE in Ontario, Canada **http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Uranium-Resources/Uranium-From-Rare-Earths-Deposits/**, accessed 7/28/15.

Potential for New Mexico REE deposits

Increasing demand for cell phones, televisions, computers, iPods, video games, wind turbines, magnets, hybrid/electric cars, and solar panels results in increased demand for more REE. Mines that can be quickly permitted and which meet current regulations will likely be the next REE producers, even if better deposits are discovered later. However, REE mines, like all mine operations, will be productive for a limited time and new resources will have to be developed to meet the demand for REE in the future. New Mexico has some deposits that are in the early exploration stage and it will take years for these deposits to be developed, if they are economic. However, it is important to understand the REE potential in New Mexico, even if deposits are not produced in the next few years, because these resources could be important in the future and it takes many years to obtain mine permits and begin production.

There are no known substitutes for REE for most applications. New research is ongoing to develop technologies that will require less REE (Gambogi and Cordier 2010). Manufacturers are finding ways to be more careful about how they use REE. Just as aluminum cans became thinner as the price of that metal soared, companies will learn to make better use of the available REE.

The best potential sources for exploration for REE in New Mexico are 1) the disseminated Y-Zr deposits in syenite are found at Pajarito Mountain, 2) carbonatites, and 3) REE-Th-U hydrothermal vein and breccia deposits, particularly in the Gallinas Mountains, Laughlin Peak, and Cornudas Mountains districts. Strategic Resources Ltd. drilled in the Lemitar Mountains in 2011 and Galinas Mountains in 2011–2012. Geovic Mining Corp. drilled in the Cornudas Mountains area in 2012. BE Resources Inc. announced that the Apache Warm Springs beryllium deposit in rhyolite contains anomalous REE (McLemore 2012), but has since dropped the project. Additional surface sampling and staking of mining claims throughout New Mexico has been done by various other companies. New Mexico pegmatites typically are too small to be currently mined for REE. However, residual placers from the pegmatites could have future potential. REE also are found in Cretaceous beach-placer sandstone deposits in the San Juan Basin in northern New Mexico, but these deposits also are too small to be mined economically today. Additional work is required on the episyenites to evaluate their potential, especially for heavy REE.

Acknowledgments

This report is part of on-going studies of mineral resources and the geology of carbonatites and alkaline igneous rocks in New Mexico, supported by the New Mexico Bureau of Geology and Mineral Resources, L. Greer Price, former Director and State Geologist. Recent research on episyenites in the Caballo and Burro Mountains was funded by the USGS Mineral Resources External Research Program (award number G12AP20051), NMBGMR, New Mexico Geological Society, and Department of Mineral Engineering (NMIMT). The NMBGMR also was recently awarded a contract by the Jicarilla Indian Tribe to examine the Cretaceous beach placer deposits at Apache Mesa near Stinking Lake, Rio Arriba County. Karen Kelly and Keith Long reviewed this manuscript and offered many suggestions to improve it. I would like to thank the many colleagues and students who contributed to and reviewed manuscripts over the years that much of this work is based upon.

References

Adams, J. W., 1965, Rare earths; in Mineral and water resources of New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 87, pp. 234–237.

Allen, M. S. and McLemore, V. T., 1991, The geology and petrogenesis of the Capitan pluton, New Mexico: New Mexico Geological Society, Guidebook 42, pp. 115–127.

Bingler, E. C., 1968, Geology and mineral resources of Rio Arriba County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 91, 158 p.

Campbell, A. R., Banks, D. A., Phillips, R. S., and Yardley, B. W. D., 1995, Geochemistry of the Th-U-REE mineralizing fluid, Capitan Mountains, New Mexico, USA: Economic Geology, v. 90, p. 1273–1289.

Castor, S. B., 2008, The Mountain Pass rare-earth carbonatite and associated ultrapotassic rocks, California: The Canadian Mineralogist, v. 46, pp. 779–806.

Castor, S. B. and Hedrick, L. B., 2006, Rare earth elements; in Kogel, J.E, Trivedi, N.C., Barker, J.M., and Krukowski, S.T., ed., Industrial Minerals volume, 7th edition: Society for Mining, Metallurgy, and Exploration, Littleton, Colorado, pp. 769–792.

Committee on Critical Mineral Impacts of the U.S. Economy, 2008, Minerals, Critical Minerals, and the U.S. Economy: Committee on Earth Resources, National Research Council, ISBN: 0-309-11283-4, 264 pp., **http://www.nap.edu/catalog/12034.html**

Cordier, D. J., 2011, 2009 Minerals Yearbook, Rare earths: U.S. Geological Survey, **http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/myb1-2009-raree.pdf** (accessed 8/20/12).

DeMark, R. S., 1980, The Red Cloud mines, Gallinas Mountains, New Mexico: Mineralogical Record, v. 11, no.2, pp. 69–72.

DeMark, R. S. and Hlava, P. F., 1993, Spangolite and other secondary minerals from the Buckhorn mine, Lincoln County, New Mexico (abstr.): New Mexico Geology, v. 15, p. 19.

Ercit, T. S., 2005, REE-enriched granitic pegmatites; in Linnen, R.L. and Samson, I.M., eds., Rare-element geochemistry and mineral deposits: Geological Association of Canada, GAC Short Course Notes 17, pp. 175–199.

Förster, H. J., 1999, The chemical composition of uraninite in Variscan granites of the Erzgebirge, Germany: Mineralogical Magazine, v. 63, pp. 239–252.

Gambogi, J. and Cordier, D. J., 2010, Rare earths: U.S. Minerals Yearbooks, 14 pp., **http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/index.html#myb**, accessed 7/28/15.

Gillerman, E., 1964, Mineral deposits of western Grant County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 83, 213 pp.

Göb, S., Gühring, J., Bau, M., and Markl, G., 2013, Remobilization of U and REE and the formation of secondary minerals in oxidized U deposits: American Mineralogist, v. 98, pp. 530–548.

Griswold, G. B., 1959, Mineral deposits of Lincoln County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 67, 117 pp.

Haxel, G. B., Hedrick, J.B., and Orris, G.J., 2002, Rare earth elements—critical resources for high technology: U.S. Geological Survey, Fact Sheet 087-02, 4 pp., **http://pubs.usgs.gov/fs/2002/fs087-02/fs087-02.pdf**

Hedrick, J. B., 2009, Rare earths (advanced release): U.S. Geological Survey, 2007 Minerals Yearbook, 20 pp.

Holmquist, R. J., 1946, Exploration of the Elk Mountain mica deposit, San Miguel County, New Mexico: U.S. Bureau of Mines, Report of Investigation 3921, 7 pp.

Houston, R.S. and Murphy, J.F., 1970, Fossil beach placers in sandstones of Late Cretaceous age in Wyoming and other Rocky Mountain states: Wyoming Geological Association, Guidebook 22, pp. 241–249.

Houston, R.S. and Murphy, J.F., 1977, Depositional environment of Upper Cretaceous black sandstones of the western interior: U.S. Geological Survey, Professional Paper 994-A pp. A1–A29.

Jackson, W. D. and Christiansen, G., 1993, International strategic minerals inventory summary report—rare-earth oxides: U.S. Geological Survey, Circular 930-N, 76 pp.

Jahns, R. H., 1946, Mica deposits of the Petaca district, Rio Arriba County, New Mexico, with a brief description of the Ojo Caliente district, Rio Arriba County and the Elk Mountain district, San Miguel County: New Mexico Bureau of Mines and Mineral Resources, Bulletin 25, 294 pp.

Jahns, R. H., 1953, The genesis of pegmatites—II. Quantitative analysis of lithium-bearing pegmatite, Mora County, New Mexico: American Mineralogist, v. 38, pp. 1078–1112.

Kelley, V. C., 1968, Geology of the alkaline Precambrian rocks at Pajarito Mountain, Otero County, New Mexico: Geological Society of America Bulletin, 79, pp. 1565–1572.

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

LeMaitre, R. W., ed., 1989, A classification of igneous rocks and glossary of terms: Blackwell Scientific Publications, Oxford, Great Britain, 193 pp.

LeMaitre, R. W., compiler, 2002, Igneous rocks: A classification and glossary of terms: Cambridge University Press, Cambridge, U.K.

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, pp. 1611–1634.

Long, K. R., van Gosen, B.S., Foley, N.K. and Cordier, D., 2010, The principle rare earth elements deposits of the United States—A summary of domestic deposits and a global perspective: U.S. Geological Survey, Scientific Investigations Report 2010–5220, 104 pp., **http://pubs.usgs.gov/sir/2010/5220/** (accessed 5/1/12).

MacDonald, G. A. and Katsura, T., 1964, Chemical composition of Hawaiian lavas: Journal of Petrology, v. 5, pp. 82–133.

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, pp. 151–159.

McLemore, V. T., 1990, Background and perspectives on the Pajarito Mountains yttrium—zirconium deposit, Mescalero Apache Indian Reservation, Otero County, New Mexico: New Mexico Geology, v. 12, p. 22.

McLemore, V. T., 1991, Pajarito Mountain yttrium–zirconium deposit, Mescalero Indian Reservation, Otero County, New Mexico: New Mexico Geological Society, Guidebook to the 42nd field conference, pp. 30–32.

McLemore, V. T., 2010a, Geology and mineral deposits of the Gallinas Mountains, Lincoln and Torrance Counties, New Mexico; preliminary report: New Mexico Bureau of Geology and Mineral Resources, Open-file report OF-532, 92 pp., **http://geoinfo.nmt.edu/publications/openfile/downloads/OFR500-599/526-550/532/ofr_532.pdf**

McLemore, V. T., 2010b, Distribution, Origin, and Mineral Resource Potential of Late Cretaceous Heavy Mineral, Beach-Placer Sandstone Deposits, San Juan Basin, New Mexico: New Mexico Geological Society Guidebook 61, pp. 197–212.

McLemore, V. T., 2011, Rare earth elements for emerging technologies: New Mexico Earth Matters, summer, 4 pp., **http://geoinfo.nmt.edu/publications/periodicals/earthmatters/11/EM11n2.pdf**

McLemore, V. T., 2012, Geology and mineral resources in the Ojo Caliente No. 2 mining district, Socorro, County, New Mexico: New Mexico Geological Society, Guidebook 63, pp. 547–558.

McLemore, V. T., 2014a, Rare Earth Elements Deposits in New Mexico, *in* Conway, F.M., ed., Proceedings of the 48th Annual Forum on the Geology of Industrial Minerals, Phoenix, Arizona, April 30–May 4, 2012. Arizona Geological Survey Special Paper #9, Chapter 3, pp. 1–16, **http://geoinfo.nmt.edu/publications/periodicals/earthmatters/11/EM11n2.pdf**

McLemore, V. T., 2014b, Geology and mineral deposits in the Capitan Mountains district: New Mexico Geological Society, Guidebook 65, pp. 60–61.

McLemore, V. T., 2015a, Great Plains Margin (alkaline-related) gold deposits in New Mexico: twenty years later: Geological Society of Nevada, New concepts and discoveries, 2015 Symposium volume.

McLemore, V. T., 2015b, Geology and Mineral Resources of The Laughlin Peak Mining District, Colfax County, New Mexico: New Mexico Geological Society, Guidebook 66, in press.

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 aulagogen: New Mexico Geological Society, Guidebook 50, pp. 247–253.

McLemore, V. T., Hoffman, G., Smith, M., Mansell, M., and Wilks, M., 2005a, Mining districts of New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Report 494, CD-ROM.

McLemore, V. T., Krueger, C.B., Johnson, P., Raugust, J.S., Jones, G. E., Hoffman, G. K. and Wilks, M., 2005b, New Mexico Mines Database: Society of Mining, Exploration, and Metallurgy, Mining Engineering, February, pp. 42–47.

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, Open-file Report OF-324, 28 pp.

McLemore, V. T., North, R.M., and Leppert, S., 1988b, Rare-earth elements (REE) *in* New Mexico: New Mexico Geology, v. 10, pp. 33–38.

McLemore, V. T. and Phillips, R. S., 1991, Geology of mineralization and associated alteration in the Capitan Mountains, Lincoln County, New Mexico: New Mexico Geological Society, Guidebook 42, pp. 291–298.

McLemore, V. T., Rämö , O. T., Heizler, M. T. and Heinonen, A. P., 2012, Intermittent Proterozoic plutonic magmatism and Neoproterozoic cooling history in the Caballo Mountains, Sierra County, New Mexico; Preliminary Results: New Mexico Geological Society, Guidebook 63, pp. 235–248.

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 pp.

Moore, S. M., Foord, E. E., Meyer, G. A., and Smith, G. W., 1988, Geologic map of the northwestern part of the Mescalero Apache Indian Reservation, Otero County, New Mexico: U.S. Geological Survey, Misc. Investigations Map I-1895, 1:24,000 scale.

Nakamura, N., 1974, Determination of REE, Ba, Fe, Mg, Na, and K in carbonaceous and ordinary chondrites: Geochimica et Cosmochimica Acta, v. 38, pp. 757–775.

Naumov, A. V., 2008, Review of the world market of rare-earth metals: Russian Journal of Non-ferrous Metals, v. 49, pp. 14-22.

Page, N. J. and Page, L. R., 2000, Preliminary descriptive model of pegmatites; *in* USGS Mineral Deposit Models: U.S. Geological Survey, Digital Data Series DDS-064, model 13, 4 pp.

Perhac, R. M., 1970, Geology and mineral deposits of the Gallinas Mountains, Lincoln and Torrance Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 95, 51 pp.

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, pp. 127–144.

Redmon, D. E., 1961, Reconnaissance of selected pegmatite districts in north-central New Mexico: U.S. Bureau of Mines, Circular 8013, 79 pp.

Riggins, A. M., 2014, Origin of the REE-bearing episyenites in the Caballo and Burro Mountains, New Mexico: M.S. thesis, New Mexico Institute of Mining and Technology, Socorro, 148 pp.

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 (abstr. and poster): Society of Economic Geology, 2014: Building Exploration Capability for the 21st Century, Program.

Rudnick, R. L. and Gao, C., 2005, Composition of the continental crust; *in* R.L. Rudnick, ed., The Crust: Treatise on Geochemistry, v. 3, Elsevier, San Diego, California, pp. 1-64.

Samson, I. M. and Wood, S., 2005, The rare-earth elements: behavior in hydrothermal fluids and concentration in hydrothermal mineral deposits, exclusive of alkaline settings; in Linnen, R.L. and Samson, I.M., eds., Rare-element geochemistry and mineral deposits: Geological Association of Canada, GAC Short Course Notes 17, pp. 269–297.

Schreiner, R. A., 1991. Preliminary investigations of rare-earth-element-bearing veins, breccias, and carbonatites in the Laughlin Peak area, Colfax County, New Mexico: U.S. Bureau of Mines, MLA 99–93, 189 pp.

Schreiner, R. A., 1993. Mineral investigation of the rare-earth-element-bearing deposits, Red Cloud Mining district, Gallinas Mountains, Lincoln County, New Mexico: U.S. Bureau of Mines, Open-file Report 2–91, 62 pp.

Schreiner, R. A., 1994. Mineral investigation of Wind Mountain and the Chess Draw area, Cornudas Mountains, Otero County, New Mexico: U.S. Bureau of Mines, MLA 26-94, 51 pp.

Shand, H. S., 1951, Eruptive rocks: 4th edition, New York, John Wiley, 488 pp.

Sheffer, H. W. and Goldsmith, L. A., 1969, Tantalum project, Rociada, New Mexico: New Mexico Bureau of Mines and Mineral Resources,

Circular 2, 15 pp.
Sherer, R. L., 1990, Pajarito yttrium-zirconium deposit, Otero County, New Mexico: New Mexico Geology, v. 12, p. 21.
Singer, D. A., 2000, Descriptive model of carbonatite deposits; in USGS Mineral Deposit Models: U.S. Geological Survey, Digital Data Series DDS-064, model 10, 3 pp.
Staatz, M. H., 2000, Descriptive model of thorium-rare-earth veins; in USGS Mineral Deposit Models: U.S. Geological Survey, Digital Data Series DDS-064, model 11d, 6 pp.
Taylor, S. R., and McClennan, S.M., 1985, The Continental Crust; its composition and evolution: Blackwell Science Publishers, Oxford, 312 pp.
USGS, 2015, Mineral commodity summaries: U.S. Geological Survey, 196 pp.
Vance, Z., 2013, Mineralogy, Geochemistry and Genesis of the Hydrothermal REE-Fluroite-AG-PB-CU Ore Deposits of the Gallinas Mountains, New Mexico [M.S. thesis]: Socorro, New Mexico Institute of Mining and Technology, 219 pp.
Verplanck, P.L., Van Gosen, B.S., Seal, R.R, and McCafferty, A.E., 2014, A deposit model for carbonatite and peralkaline intrusion-related rare earth element deposits: U.S. Geological Survey Scientific Investigations Report 2010–5070-J, 58 pp.
Woolley, A. R. and Kempe, D.R.C., 1989, Carbonatites: Nomenclature, average chemical compositions and element distribution; in Bell, K., ed., Carbonatites: Genesis and Evolution: Unwin Hyman, London, pp. 1–14.
Zech, R. S., Reynolds, R. L., Rosenbaum, J. G., and Brownfield, I. K., 1994, Heavy-mineral placer deposits of the Ute Mountain Ute Indian Reservation, southwestern Colorado and northwestern New Mexico: U.S. Geological Survey, Bulletin 2061-B, 39 pp.

Gallery of Geology

Bastnäesite

Bastnäsite [chemical formula is $(Ce,La)(CO_3)F$] in the Red Cloud deposit, Gallinas Mountains district, Lincoln County, New Mexico (length is ~8 mm). Bastnäsite is the most common REE mineral mined in the world today.

William Richard Dickinson (1931–2015)
A Personal Farewell

Timothy F. Lawton, Centro de Geociencias
Universidad Nacional Autónoma de México, Querétaro, 76230, México

Bill and Jackie Dickinson on an Arizona Geological Society field trip in 2010. Photo courtesy of Karen Wenrich.

Introduction

With the passing of Bill Dickinson in mid-July, the geologic community of New Mexico, and everywhere else, lost an enduring colleague and friend. By a remarkable combination of intellect, self-confidence, engaging humility, and prodigious output of published work, he influenced and challenged (to date) three generations of geoscientists and other researchers—sedimentary geologists, igneous petrologists, tectonicists, sandstone petrologists, archeologists and university students, to list a few categories—around the globe. Bill looms large on the geologic landscape of western North America and surely the Big Book on Cordilleran Tectonics contains a longish chapter entitled "The Life and Times of Bill Dickinson." To summarize that chapter in a few pages might be considered foolish; if so, consider the following a momentary lapse of reason.

Career Trajectory

The wide and varied path of Dickinson's career is challenging to tread even in retrospect, and impossible to have even guessed at in advance; in some phases, it seems to have followed a rational, single sequence of themes that grew upon one another in an evolutionary fashion, but further study shows that seemingly disparate, yet parallel scientific disciplines were deliberately woven together to gain new traction on unsolved problems and in the doing yielded new fields of scientific endeavor. This ability to meld unrelated disciplines constitutes the fabric of genius. It would be impossible to look at the accomplishments from a single phase of his research lifetime and predict from that phase the direction of a particular path into the future, or even to hindcast the beginnings. I divide his lifetime into the Early Years, Stanford, Arizona, and a protracted triumphant phase of hyperactive retirement. Some of these recollections are in his own words and others are as I recall the conversations. The scientific accomplishments and recognitions of them are a matter of public record.

Prelude

Bill was born in Nashville, Tennessee. His parents raised horses, and he learned to ride before moving, as a teenager, with the family to California. As an undergrad at Stanford, he spent every Christmas and Spring vacation packing through the western Transverse Ranges with friends, during a time when he kept a riding horse and packhorse at a ranch on the Santa Ynez River. He spent summer breaks on the Colorado Plateau, operating out of Bluff, Utah, as a participant and later a counselor at Explorer's Camp, run by Kenny Ross, who later founded a river running company called Wild Rivers. The camp was a horseback forerunner of Outward Bound, but as Bill put it, "way more hard-core." He ran some rivers during that time, and participated in the first traverse of Cataract Canyon in inflatable rafts in 1949. There is an inset photo near mile 199 of the Colorado River strip map in the first edition of Bill Belknap's *Canyonlands River Guide* that shows two young men with paddles, in the back of a 12-foot military inflatable, working furiously through some rough water. The caption, which reads "The Big Drop. Rapid 23 paddled by Ken Ross and Jon Lindbergh. 4 September 1949," is evidently improperly attributed, because Bill once pointed out the photo in his copy of the guide and observed, "That's Kenny and me in the boat."

The river days fostered his interest in earth processes and honed his common sense. On one San Juan River trip, he was fascinated by sand waves on the lower stretch of the river, now beneath Lake Powell, downstream of the Goosenecks and so naturally he tied himself on the end of a rope, had some friends hold the line, and swam out into the current above the rapid to investigate. He drifted downstream into the haystacks and, although wearing a flotation device of some type, he jerked to a halt at the end of his rope and suddenly found himself "plastered firmly against the sandy bottom," unable to move or do anything to save himself. The guys holding the rope were similarly befuddled by his abrupt disappearance and briefly held their ground, bracing themselves against the taut line. After a moment, one of them regained enough composure to holler that they should let go of the rope. They did, Bill popped up, floated out the rest of the rapid and swam back to shore, a life saved and a lesson learned.

He possessed two different voices. For one, there was Dickinson the orator and professor, a persona for which he had a full and resonant, commonly booming, voice. As an orator, he had a powerful capacity to communicate his views, a capacity that stemmed in part from articulate phrasing and an enormous vocabulary, some of it invented, in part from a willingness to discuss his thoughts, in depth, wherever and whenever, and in part from a perception among those in the discussion that their interpretations were taken seriously. He listened intently, evaluated message content, and if he demurred, was quick to point out flaws in an argument, all in real time, and in a completely relaxed manner. Second, there was Bill the raconteur. He loved to tell a tale, and he fell into another voice for story telling or for describing what he considered the interpretive dead ends of others, which were generally amusing to him. That voice was higher by an octive and raspy, and grew ever more wheezy as the story progressed and he became more amused, his face broadening into a huge grin and his eyes glittering slits as he leaned into the listener, his hands planted firmly on the desk or table, or if space permitted, his arms spread just short of full span and his fingers fully splayed. His tales were pure Huck Finn, but usually possessed plots and conclusions.

Stanford

Bill received three degrees from Stanford University, a B.S. in Petroleum Engineering, and M.S. and Ph.D. in Geology. As an undergraduate at Stanford, Dickinson was at the beginning a "disgruntled" engineering major, "a duck out of water," he once wrote with his life-long penchant for re-invented metaphors. In the spring quarter of his junior year, he took a course called Geology for Engineers from Dr. Aaron Waters. His "Eureka moment" came on a class field trip to Half Moon Bay, just across the coastal hills from campus, when it struck him that "a guy might be able to make a living doing that sort of thing." He claimed to have never looked back after that day.

He became an acting assistant professor at Stanford in 1958, when he began the first phase of his academic career studying the geology of active margins. A scientific revolution was newly underway as geosynclines fell to the logic of the new global tectonics, and Dickinson was immediately a proponent of the new ideas. In 1964, he received a Guggenheim Fellowship to investigate volcaniclastic sedimentation in the Neogene succession of Fiji. Scientific contributions during that time began with analysis of the genetic relations of andesites to subduction zones (Dickinson and Hatherton, 1967), and evolved quickly to the role of sedimentary basins in the gap between the trench and the magmatic arc (Dickinson, 1970b). He convened a legendary Penrose Conference on Plate Tectonics and Orogenic Belts at Asilomar, California in 1969, edited an SEPM Special Paper entitled "Tectonics and Sedimentation" (Dickinson, 1974), and devised a genetic classification of sedimentary basins according to their positions with respect to plate boundaries (Dickinson, 1976). Although much embellished, the latter scheme has been little modified in the intervening years. To the end of his days, a deliberately broken and repaired ceramic dinner plate with signatures of the participants from the Asilomar Conference hung on his various office walls. Years later, Eldridge Moores, another major influence in Cordilleran tectonics, recalled of the Penrose Conference (Moores, 1999):

> "At the meeting, the full import of the plate tectonic revolution burst upon the participants like a dam failure. Dickinson's final day summation of the relationship between active tectonic environments and sedimentation (subsequently published as Dickinson, 1971, 1972) administered what seemed at the time to be the final *coup de grace* to the old geosynclinal concept. I remember it as one of the most exciting scientific moments of my life!"

He married Jacqueline (Jackie) Spencer in 1970, and they were inseparable traveling companions from that time on.

Parallel with his research on andesites, he developed an intense interest in sandstones derived from volcanic rocks and how the general composition of sedimentary-basin fill might record plate-tectonic setting. In order to better understand how sandstone compositions reflected the tectonic setting of a basin, and hence its geotectonic significance, he learned how to see through the complicated alteration patterns of lithic sandstones to get at original composition (Dickinson, 1970a). I learned early in our association never to use the term *greywacke*. He also developed a point-counting method for systematic petrographic analysis of sandstones, a technique that reduced an inherent bias introduced into count results by grain-size variation in different samples. Because an Italian petrographer independently developed a similar methodology at the same time, the counting technique is to this day known as the "Gazzi-Dickinson" method (Ingersoll et al., 1984). The compositional analysis of sandstones led to a series of papers by Bill and his graduate students, culminating in a synthesis of extant compositional data entitled "Plate Tectonics and Sandstone Composition," published in AAPG Bulletin (Dickinson and Suzcek, 1979). At the time, it was axiomatic that most sedimentary petrologists of the latter 20th Century came from established lineages, schools of thought that arose in centers of excellence in the East and Midwest and extended back to the beginning of the century, or earlier. Lacking such a pedigree, but familiar with the extant literature, and necessity being the mother of invention, Bill simply puzzled out a method to get good reproducible results, whether by a single operator, or multiple investigators working on a single project (see Graham et al., 1976). A member of one of the established academic lineages at UT Austin once asked me, completely seriously, "Where did he come from?"

University of Arizona

In 1979, Bill moved from Stanford to the University of Arizona in Tucson, where he and Jackie bought a small home in what was then the rural north side of town, overlooking River Road and the dry Rillito River. Together with Peter Coney, he founded the Laboratory of Geotectonics, which expanded and complemented an already-powerhouse Department of Geosciences with strengths in mining geology, structural geology, igneous petrology and paleontology. He delved enthusiastically into the regional geology of southern Arizona, and within a decade, with the help of a small army of students, had made inroads into the little-understood Bisbee Basin and Miocene basins associated with development of the only recently elucidated core complexes. Characteristically, he referred to the Miocene gravel deposits as the "Chimichanga Conglomerates," because "Everywhere these rocks crop out, throughout their range of distribution, you can always find yourself a great chimichanga for dinner." He applied plate-tectonic logic to the southwestern part of Laurentia, which resulted in an influential compilation of papers under the title, "Relations of tectonics to ore deposits in the southern Cordillera," published by the Arizona Geological Society (Dickinson and Payne, 1981). At UA, Bill championed the concept of the pre-publication MS thesis, an article-length work, in lieu of the more traditional black book; consequently, the early years at UA yielded an edited volume on the Mesozoic Rocks of southern Arizona, principally containing papers authored by student advisees and their contemporary colleagues (Dickinson and Klute, 1987), as well as a monograph on Miocene sedimentation associated with the core complex of the Catalina Mountains (Dickinson, 1991). Although he once offered a rather flimsy explanation for his departure from Stanford by claiming, "I painted myself into a corner in California geology," he continued to publish syntheses on the Mesozoic evolution of California (e.g., Dickinson et al., 1982; Dickinson, 1983).

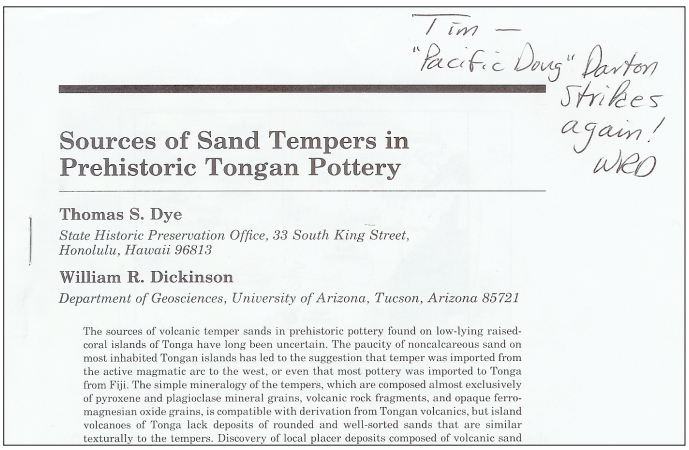
In addition to a new house, the other thing Bill purchased upon arriving in Tucson was a 1978 Ford F-150 pickup. It was fire engine red, big with a white camper, had four-wheel drive and the economical, rectilinear lines characteristic of the era. During the 1980s he and Jackie became regular participants at Annual NMGS Fall Field Trips, and the Red Ford was a conspicuous component of the annual vehicle caravan. It had a bench seat with plenty of room for three people, and Jackie was always there, in the middle if there was an extra rider, which was usually the case. Over the years, the pickup traveled to more places in the western U.S. than most of us can find on Google Earth, and Bill once claimed, "It's the last truck I'll ever buy." In truth, I think it might have been his first truck as well. Then, not long after he retired, it was stolen from a UA parking garage. After several days, resigned to its loss, he put the truck title in an envelope, ready to mail it next day to the insurance company. At literally the eleventh hour, the Phoenix Police Department called to say the truck had been recovered at a local chop shop. The thieves had removed the VIN tag from the Ford's dashboard, but had overlooked an identification plate on the chassis, evidently a common oversight. His truck came home with new chrome rims, a chrome tailgate strip, and the desert pin striping gone, buffed out of the paint job. It was a brand new ride. He put stock wheels back on but kept the chrome strip. Despite his claim of undying loyalty to the Red Ford, it accumulated a lot of miles in the

pursuit of so much western geology, eventually got road weary, and the Dickinsons finally showed up in a brand-new blue Ford pickup at the NMGS Chama Basin trip in 2005. That marked the end of an era, but I'm ahead of myself.

At about the time he arrived in Tucson, Bill's attention returned to the Colorado Plateau. I take some credit for that, in a convoluted way: In the spring of 1978, I attended a Pacific Section SEPM meeting in Sacramento, full of talks about the paleogeography and evolution of the Sierra Nevada derived from study of stratigraphy and sedimentary basins through time. It was a tough interpretive row to hoe, in part because of intense deformation characteristic of the Sierran foothills and attendant problems determining the age of complex accretionary rocks there. Rich Schweikert, one of Bill's former students, did an impromptu chalk talk, without benefit of slides, on how the Laytonville Limestone in the Franciscan Formation might be the deposit of a volcanic atoll, traveled to the margin from somewhere far out in the Pacific, a stupendous suggestion. The meeting atmosphere was electric, charged with excitement that comes from new insights deriving from novel approaches to vexing problems. The next morning I bounded into Bill's office: "I know what we can do! We can go out behind the arc, to the east, and study the basins where they aren't all messed up. Do the sandstone petrology and all that."

He gave me a brief thoughtful gaze, and said, "Great idea, Sport, but there ain't no basins out there." That was about the extent of the response, and relying on his encyclopedic knowledge of the Cordillera for instant on-site analysis, my reaction was even shorter."Oh." I shuffled out of the office, feeling a little dejected.

A couple of days later, a slip of paper appeared in my mailbox with a handwritten note summoning me back to the office, where Bill was energized.
"We can study the foreland basin in Utah," he reprised the earlier short conversation. "It's not right behind the arc, but no one has looked at the sandstone composition there yet."


Tim —
"Pacific Doug" Darton
Strikes
again!
WRD

Sources of Sand Tempers in Prehistoric Tongan Pottery

Thomas S. Dye
State Historic Preservation Office, 33 South King Street, Honolulu, Hawaii 96813

William R. Dickinson
Department of Geosciences, University of Arizona, Tucson, Arizona 85721

The sources of volcanic temper sands in prehistoric pottery found on low-lying raised-coral islands of Tonga have long been uncertain. The paucity of noncalcareous sand on most inhabited Tongan islands has led to the suggestion that temper was imported from the active magmatic arc to the west, or even that most pottery was imported to Tonga from Fiji. The simple mineralogy of the tempers, which are composed almost exclusively of pyroxene and plagioclase mineral grains, volcanic rock fragments, and opaque ferromagnesian oxide grains, is compatible with derivation from Tongan volcanics, but island volcanoes of Tonga lack deposits of rounded and well-sorted sands that are similar texturally to the tempers. Discovery of local placer deposits composed of volcanic sand

The Upper Cretaceous of Utah it was. When I arrived in Tucson in July 1980, in the middle of the most hellacious heat humanity can possibly endure and wondering what and where I had committed to, the three of us hopped into the Red Ford and drove north to cooler weather, through Arizona, southeastern Utah, and into the thrust belt of central Utah, reading the stratigraphy all the way. I learned more regional stratigraphy in those two weeks than in any comparable interval of time since and I began to comprehend a new approach to it. I had seen most of those rocks during my own river years, but the Dickinson lens provided an entirely new way of appreciating strata. That project yielded a handful of papers about the foreland depositional system, including an analysis of Cretaceous-Paleocene sediment-dispersal pathways in the foreland basin (Dickinson et al., 1986). I went off to work and he went on to other things, it seemed, but the plateau ideas fermented.

On the trip to the plateau, Bill developed a third persona, this one an alter ego for which he actually had a name. He referred to this muse as "W.D. Darton," or "W. Doug Darton," or simply "Darton." This guy was a smart, yet mischievous fellow who surfaced from time to time in stories or field events when Bill needed a historical source for which he didn't have a ready attribute, for instance, the discoverer of a small arch we encountered during the trip. The surname was no doubt inspired by the great N.H. Darton of New Mexico fame, but the source of the given names remains a mystery to me. The younger Darton turns up a few times in the acknowledgments sections of papers published in the 1980s, and elsewhere (see figure below).

During his tenure at the University of Arizona, Bill served as general chair of the Annual GSA Meeting in Phoenix (1987) and was head of the Department of Geosciences from 1986–1991. When he began as department head, his annual salary, although not staggering by today's standards, was deemed adequately newsworthy to be published in the Arizona Daily Star. Then, in 1991, he retired from active teaching. By that time, in the span of about 30 years, he had advised some 85 graduate students, almost equally divided between M.S. and Ph.D. degrees.

Retirement

His retirement was quickly noted by the scientific community, although somewhat atypically. In 1992, Bill was elected to the National Academy of Sciences. In 1993, he became President of the Geological Society of America. But perhaps most significantly, he teamed up with George Gehrels, a young structural geologist and geochronologist in the department, to tackle the provenance of sandstones in an entirely new way. Dickinson was smitten by the promise of a new technique for determining the ancestry of resistant zircon grains found in sandstones. The zircon grains, chemically and mechanically resistant in the sedimentary cycle, contain small amounts of uranium that permit age determination of individual grains by decay to lead. He bemoaned the lack of funding for the early work; grain analyses were performed by laborious single-grain dissolution and generally reported in numbers of thirty or fewer zircon grains. Reviewers, accustomed to the probability statistics of traditional petrographic provenance methods provided by counting 400 grains, balked at the proposals floated by Bill and George. They began their work on some problematic Paleozoic units in the Great Basin (Gehrels and Dickinson, 1995) and provided proof of concept: Some grain assemblages definitely came from Laurentia, whereas others in accreted rocks were difficult to attribute to known continental basement sources. Subsequent work in the Basin and Range again employed teams of students, undergraduates this time around, and generated an impressive body of data (Gehrels and Soreghan, 2000). When they eventually secured NSF funding, Bill expressed profound relief in part because it validated his decision to retire, and with the development of more rapid laser-ablation techniques for analyzing zircon grains, the colleagues took on the depositional systems of the Colorado Plateau, ranging from the late Paleozoic through the Late Cretaceous. This work, probably the best known among younger geologists, resulted in a stack of papers that documented transfer of huge volumes of sand from the eastern to the western margin of Laurentia during Permian, Triassic and Jurassic time (Dickinson and Gehrels, 2008b, 2009; Gehrels et al., 2011, among others), and described evolving dispersal systems of the Cordilleran foreland from Late Jurassic through Late Cretaceous time (Dickinson and Gehrels, 2008a). Thus was born another field of endeavor. The development of better laboratory facilities and faster analytical techniques at the University of Arizona, George's *forte*, coupled with procedures for analyzing and interpreting the huge amounts of data that began to flow from the lab, Bill's contribution, inspired a renaissance in provenance studies and their implications for mega-paleogeography. These studies, practiced by legions of workers who would never dream of looking through a microscope at a

sandstone, promise better access to ancient continent- and supercontinent-scale river systems and better attendant plate reconstructions back into the Proterozoic. During this period of time, he also undertook syntheses of the North American Cordillera (Dickinson, 2004) and the Basin and Range region (Dickinson, 2006, 2011).

Bill had a parallel scientific career that many of his colleagues and associates likely learned about from reading his obituaries. Beginning in 1966, complementary with his interest in orogenic andesites, he began a systematic study of sand tempers in potsherds recovered from prehistoric ceramic sites in Oceania, a region of the southwest Pacific spread across 6,500 km from Belau, Yap and the Marianas north of New Guinea to French Polynesia on the east. He examined 1558 thin sections of pottery fragments from sites on nearly 100 islands or island clusters spanning ten major island groups. By 2009, traveling to the South Pacific each summer to visit different islands, he and Jackie had visited more than 120 islands. Notably, his first publication on temper composition (Dickinson and Shutler, 1968) appeared before any of his analyses of synorogenic sandstones. This line of investigation defined groups of temper types derived from different island groups having distinctive petrologic characteristics as a result of their differing plate-tectonic settings and resulted in more than 40 publications on the composition of sherd tempers (Dickinson and Shutler, 2000 and references cited therein). He could recognize sand, for example, from Fiji, or Tonga, or the Solomon Islands. Using petrographic skills and methods devised for the study of sandstone, Bill and colleagues discerned trade routes of colonizing Polynesians between islands, but a key insight was that much of the pottery was indigenous, constructed of local clay and temper, and that (and I can see the wide grin as I read this passage):

> *"Ancient potters were so resourceful in identifying and exploiting rare but readily available raw materials that it has taken investigators more than a quarter century to understand where they found their tempers. Therein may be a moral of lasting importance for future archaeological interpretation in the Pacific region, and especially for those that posit transport of materials over long distances based on the apparent lack of suitable materials locally.....*
> *"In seeking the locations of ceramic resources on Pacific islands, future investigators should credit ancient potters with a detailed knowledge of local environmental constraints at a level difficult to replicate in hindsight (Dye and Dickinson, 1996, p. 161)."*

His South Pacific research, which also included later analysis of the history and mechanisms of island sea-level change, resulted in a body of work impressive in its own right, for which he received the Rip Rapp Archaeological Geology Award, the Archeological Geology Division's top award, at the GSA 2014 Annual Meeting in Vancouver. He also received several other top society awards for his body of work, from the GSA Sedimentary Geology Division (Sloss Award, 1999), SEPM (Twenhofel Medal, 1999), and from GSA itself (Penrose Medal, 1991). But for all this recognition, he never stopped attending regional meetings and field trips, such as those offered by the Utah Geological Association, the Geological Society of Nevada, and the New Mexico Geological Society, because his roots lay in field geology. He participated actively in those meetings, such as on the Fall Field Conference of the Utah Geological Association in 2010, about which he wrote as he was planning to depart for the field trip:

"On the UGA trip I get to spiel about DZ at that wonderful overlook of all the Navajo slick rock country just east of Escalante. I plan to start by quoting the old poem:

> *'Breathes there the man with soul so dead*
> *Who never to himself hath said*
> *This is my own my native land'*
>
> [the joy of wildlands angle], and then say
>
> *'Breathes there the geologist with soul so dead*
> *Who never to himself hath said*
> *I wonder where the hell all that quartz came from'*
>
> [the fun of science angle]. The two together is the perfect formula for life."

CODA

Bill Dickinson has been called a giant in tectonics and sedimentation and the tectonics of the Cordilleran, but what makes a giant? Although the formula varies, intellectual influence of his caliber requires a combination of genius, strong inference, communication skills, accessibility, and productivity. Geology was Bill's profession, his pursuit, and his passion. There was nothing magical about his method: He would select a topic, drive down to the University of Arizona library for the day and read about it, then return home in the evening with a sheaf of longhand written lined pages. The analysis was copy ready, containing observations and interpretations by the authors as well as Bill's own inferences. All trips with Jackie, be they apparent vacations to the South Pacific or camping trips to the Colorado Plateau, were working field trips. He couldn't not work. As he once remarked, "Where else but the South Pacific can you be walking down the stairs from the airplane, flip open your notebook, and start writing?" The short answer is it would probably be easy for most pilgrims visiting a remote tropical island.

His love for the South Pacific explains the location of his unexpected mid-summer death in Tonga, where he was conducting fieldwork with a team of archeologists. As it happens, Jackie, his constant companion of over 40 years, passed away in Tucson in May, preceding him in death by just two months. He was buried in Tonga at Mala'e Sia Cemetary in the village of Nukuleka, Tongatapu, on Sunday August 2, becoming part of an island legacy he helped to discover. In conclusion, one can't help but wonder if he deliberately picked a place just the other side of the International Date Line to get the earliest start possible on whatever adventure comes next.

Acknowledgments

I thank Alan Herring and Jon Spencer for some of the critical dates and locations included in the text.

References Cited

Dickinson, W.R., 1970a, Interpreting detrital modes of graywacke and arkose: Journal of Sedimentary Petrology, v. 40, pp. 695–707.
Dickinson, W.R., 1970b, Relations of andesites, granites and derivative sandstone to arc-trench tectonics: Reviews of Geophysics and Space Physics, v. 8, pp. 813–860.
Dickinson, W.R., 1971, Plate tectonic models of geosynclines: Earth and Planetary Science Letters, v. 10, pp. 165–174.
Dickinson, W.R., 1972, Evidence for plate-tectonic regimes in the rock record: American Journal of Science, v. 272, pp. 551–576.
Dickinson, W.R., 1974, Plate tectonics and sedimentation, in Dickinson, W. R., ed., Tectonics and Sedimentation, Society of Economic Paleontologists and Mineralogists Special Publication 45, pp. 1–27.
Dickinson, W.R., 1976, Plate-tectonic evolution of sedimentary basins: American Association of Petroleum Geologists, Continuing Education Course Note Series 1, 62 pp.
Dickinson, W.R., 1981, Plate tectonic evolution of the southern Cordillera, in Dickinson, W. R., and Payne, W. D., eds., Relations of tectonics to ore deposits in the southern Cordillera, Volume 14, Arizona Geological Society Digest, pp. 113–135.
Dickinson, W.R., 1983, Cretaceous sinistral strike slip along Nacimiento fault in coastal California: American Association of Petroleum Geologists Bulletin, v. 67, pp. 624-645.

Dickinson, W.R., 2004, Evolution of the North American Cordillera: Annual Review of Earth and Planetary Science Letters, v. 32, pp. 13–45.
Dickinson, W.R., 2006, Geotectonic evolution of the Great Basin: Geosphere, v. 2, pp. 353–368.
Dickinson, W.R., 2011, The place of the Great Basin in the Cordilleran orogen, in Steininger, R., and Pennell, B., eds., Great Basin evolution and metallogeny: Reno, Geological Society of Nevada 2010 Symposium, pp. 419–436.
Dickinson, W.R., and Gehrels, G.E., 2008a, Sediment delivery to the Cordilleran foreland basin: Insights from U-Pb ages of detrital zircons in Upper Jurassic and Cretaceous strata of the Colorado Plateau: American Journal of Science, v. 308, pp. 1041–1082.
Dickinson, W.R., and Gehrels, G.E., 2008b, U-Pb ages of detrital zircons in relation to paleogeography: Triassic paleodrainage networks and sediment dispersal across southwest Laurentia: Journal of Sedimentary Research, v. 78, pp. 745–764.
Dickinson, W.R., and Gehrels, G.E., 2009, U-Pb ages of detrital zircons in Jurassic eolian and associated sandstones of the Colorado Plateau: Evidence for transcontinental dispersal and intraregional recycling of sediment: Geological Society of America Bulletin, v. 121, pp. 408–433; doi: 410.1130/B26406.26401.
Dickinson, W.R., and Hatherton, T., 1967, Andesitic volcanism and seismicity around the Pacific: Science, v. 157, pp. 801–803.
Dickinson, W.R., and Klute, M.A., eds., Mesozoic rocks of southern Arizona and adjacent areas: Arizona Geological Society Digest, v. 18, 394 pp.
Dickinson, W.R., and Shutler, R., Jr., 1968, Insular sand tempers of prehistoric pottery from the southwest Pacific, in Yawata, I., and Sinoto, Y. H., eds., Prehistoric culture in Oceania: Honolulu, Hawaii, Bishop Museum Press, pp. 29–37.
Dickinson, W.R., and Shutler, R., Jr., 2000, Implications of petrographic temper analysis for Oceanian prehistory: Journal of World Prehistory, v. 14, pp. 203–266.
Dickinson, W.R., and Suczek, C.A., 1979, Plate tectonics and sandstone compositions: American Association of Petroleum Geologists Bulletin, v. 63, pp. 2164–2182.
Dickinson, W.R., Lawton, T.F., and Inman, K.I., 1986, Sandstone detrital modes, central Utah foreland region: Stratigraphic record of Cretaceous-Paleogene tectonic evolution: Journal of Sedimentary Petrology, v. 56, pp. 276–293.
Dye, T.S., and Dickinson, W.R., 1996, Sources of sand tempers in prehistoric Tongan pottery: Geoarcheology: An International Journal, v. 11, pp. 141–164.
Gehrels, G. E., and Dickinson, W. R., 1995, Detrital zircon provenance of Cambrian to Triassic miogeoclinal and eugeoclinal strata in Nevada: American Journal of Science, v. 295, pp. 18–48.
Gehrels, G. E., Blakey, R., Karlstrom, K. E., Timmons, J. M., Dickinson, B., and Pecha, M., 2011, Detrital zircon U-Pb geochronology of Paleozoic strata in the Grand Canyon, Arizona: Lithosphere, v. 3, pp. 183–200.
Soreghan, M. J., and Gehrels, G. E., eds., Paleozoic and Triassic paleogeography and tectonics of western Nevada and northern California, Geological Society of America Special Paper 347, 252 pp.
Graham, S. A., Ingersoll, R. V., and Dickinson, W. R., 1976, Common provenance for lithic grains in Carboniferous sandstones from Ouachita Mountains and Black Warrior basin: Journal of Sedimentary Petrology, v. 46, pp. 620–632.
Ingersoll, R. V., Bullard, T. F., Ford, R. L., Grimm, J. P., Pickle, J. D., and Sares, S. W., 1984, The effect of grain size on detrital modes: A test of the Gazzi-Dickinson point-counting method: Journal of Sedimentary Petrology, v. 54, pp. 103–116.
Moores, E.M., 1999, William R. Dickinson, in Moores, E.M., Sloan, D. and Stout, D.L. (eds.), Classic Cordilleran Concepts: A View From California: Geological Society of America Special Paper 338, p. 6.