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HEAVY MINERAL, BEACH-PLACER SANDSTONE DEPOSITS AT APACHE MESA, JICARILLA APACHE RESERVATION, RIO ARRIBA COUNTY, NEW MEXICO

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Abstract—Cretaceous heavy mineral, beach-placer sandstone deposits are found in the Point Lookout Sandstone on the Jicarilla Apache Reservation, Rio Arriba County, New Mexico. Beach-placer sandstone deposits are characterized by relatively high accumulations of heavy, resistant minerals (i.e., high specific gravity) that form on the upper regions of beaches or in long-shore bars in a marginal-marine environment. They form by mechanical concentration (i.e., settling) of heavy minerals by the action of waves, currents, and winds. Modern examples are found along the Atlantic Coast in the United States, southeastern Australia, and Andhra Pradesh in India, where these deposits are mined for titanium, zircon, and locally, monazite (a Ce-bearing rare earth elements mineral). Other potential commodities include niobium, chromium, thorium, and rare earth elements (REE). The Apache Mesa beach-placer sandstone deposits are similar in origin, texture, mineralogy, and chemical composition to beach-placer sandstone deposits elsewhere in the San Juan Basin and in the world. The Apache Mesa beach-placer sandstone deposit contains only 132,900 short tons (120,564 metric tons) of ore with grades of 3% TiO_2, 108 ppm Cr, 46 ppm Nb, 2,187 ppm Zr, 40 ppm Th, and 522 ppm total REE. Modern, economic beach-placer sandstone deposits are typically greater than 10 million short tons of greater than 2% heavy minerals and are mined by open-pit methods. Geologic mapping and drilling indicate that the Apache Mesa beach-placer sandstone deposits are too small and low grade to be economic in today's market. No further investigation is recommended at this time.

INTRODUCTION

This paper summarizes an investigation of the geology and economic viability of heavy mineral, beach-placer sandstone deposits in the Cretaceous Point Lookout Sandstone at Apache Mesa, located on the eastern margin of the San Juan Basin, New Mexico. The Point Lookout Sandstone, along with other Cretaceous nearshore transgressive or regressive deposits in the San Juan Basin, locally host beach-placer sandstone deposits. Beach-placer sandstone deposits are accumulations of heavy, resistant minerals (i.e., high specific gravity) that form on the upper regions of beaches or in long-shore bars in a marginal-marine (nearshore) environment. They form by mechanical concentration (i.e., settling) of heavy minerals by the action of waves, currents, and winds (Fig. 1; Bryan et al., 2007; van Gosen et al., 2014). Specifically beach-placer sandstones form in the upper part of the high-tide swash (wave) zone and in the foreshore zone where they are remobilized by winds and waves, especially after storm surges (van Gosen et al., 2014).

Modern examples of beach-placer sandstones are found along the Atlantic Coast in the United States (Koch, 1986; Carpenter and Carpenter, 1991; Pirkel et al., 2009), Oregon (Peterson et al., 1986), southeastern Australia (Roy, 1999; Reid et al., 2013), west coast of South Africa (Philander and Rozendall, 2015), Tartous in Syria (Kattaa, 2002), and Andhra Pradesh in India (Rao et al., 2008). In these localities, beach placers are mined for titanium-bearing minerals, zircon, and locally, monazite (a Ce-bearing rare earth elements mineral). Other potential commodities include niobium, chromium, thorium, and rare earth elements (REE). In most of these localities, detrital heavy minerals comprise approximately 50–60% of the sandstone and typically include titanite, zircon, magnetite, ilmenite, monazite, apatite, rutile, xenotime, garnet, allanite, and other heavy minerals. Most of these minerals have a high specific gravity that exceeds 4 and are dark colored, giving the sandstones a dark color, resulting in them also being called black sandstones. Beach-placer sandstones have been found elsewhere, such as south Texas (Shelby, 1965), but were not high enough grade to be economic.

Although beach-placer sandstone deposits are found in strata of all ages, the deposits in the San Juan Basin in New Mexico are restricted to Late Cretaceous rocks belonging to the Gallup, Dalton, Point Lookout, and Pictured Cliffs Sandstones (Fig. 2; Murphy, 1956; Allen, 1956; Chenoweth, 1957; Houston and Murphy, 1970, 1977; Brookins, 1977; McLemore, 2010; Mc-

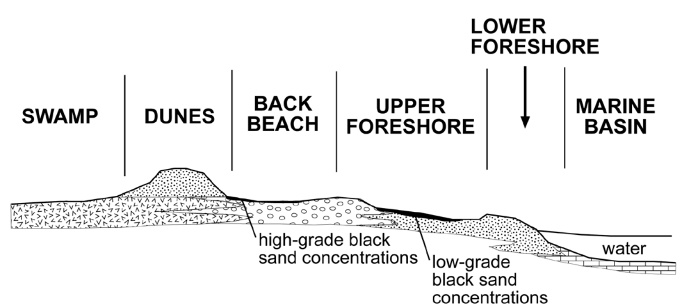


FIGURE 1. Idealized cross-section of formation of heavy mineral, beach-placer sandstone deposits (Houston and Murphy, 1970, 1977).

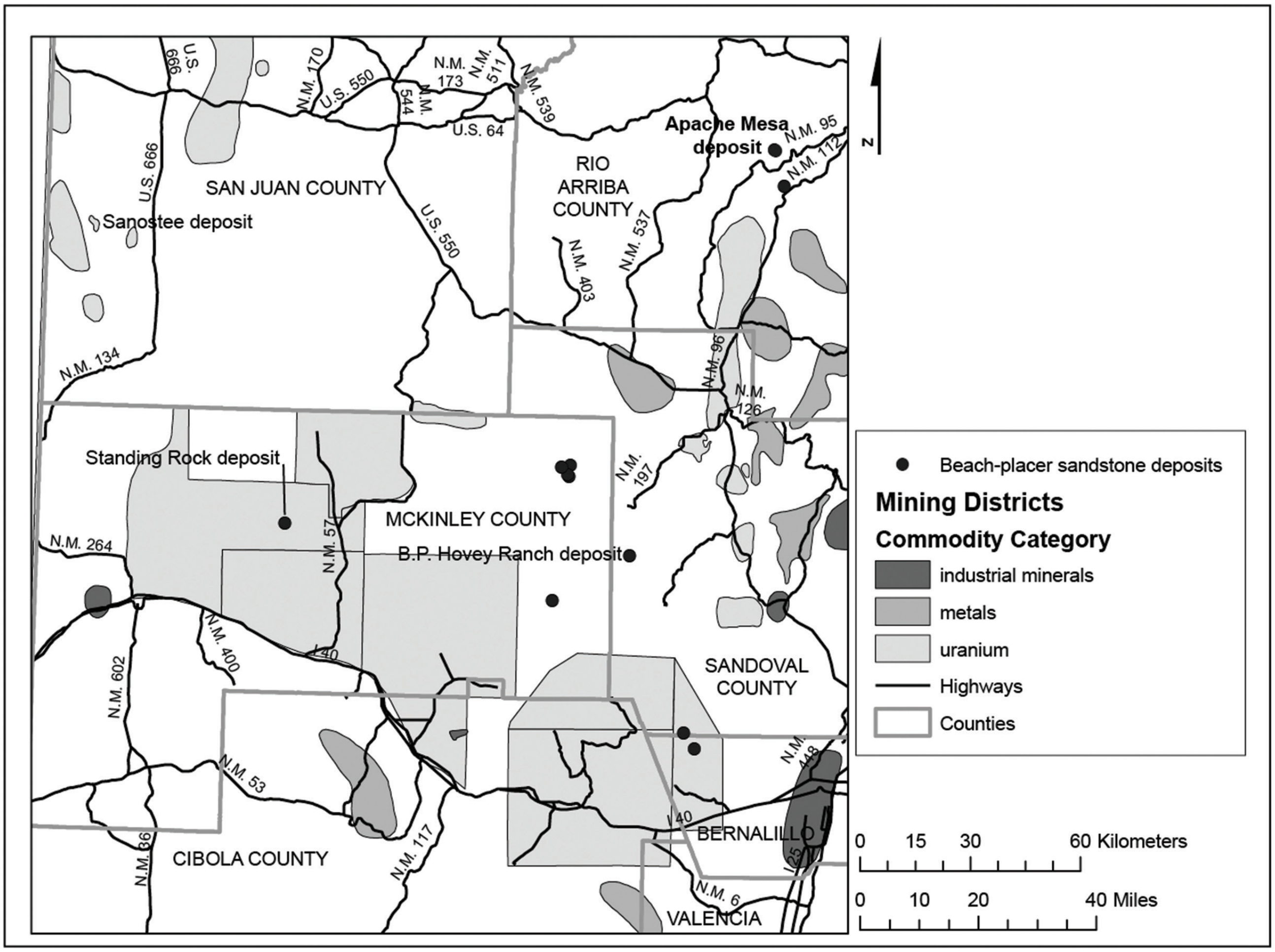


FIGURE 2. Location of Late Cretaceous heavy mineral, beach-placer sandstone deposits in the San Juan Basin, New Mexico. Deposits are described in McLemore (2010) and McLemore et al. (2016).

Lemore and Robinson, 2016; McLemore et al., 2016). These formations are characterized by nearshore facies deposited during transgressions and regressions of the Western Interior Seaway. The beach-placer sandstones locally hosted in these formations in New Mexico are black to dark gray to olive-brown, resistant to erosion, and contain radioactive minerals, such as zircon, monazite, apatite, and thorium-bearing minerals. Anomalously high concentrations of titanium, iron, niobium, thorium, uranium, zirconium, scandium, yttrium, and REE are typical of these deposits. Similar Upper Cretaceous heavy mineral, beach-placer sandstone deposits are found throughout Montana, Wyoming, Utah, Arizona, and Colorado (Dow and Batty, 1961; Houston and Murphy, 1970, 1977; Zech et al., 1994).

Many of the elements potentially found in beach-placer sandstone deposits, especially titanium and REE (including yttrium and scandium), are increasingly becoming more important in our technological society and are used in many of our electronic devices (Morteani, 1991; Long et al., 2010; McLemore, 2011, 2015). The white color and high refractive index of titanium make it an important ingredient in pigment in paint, plastics, and paper (Force, 1991, 2000; Jones, 2009). Zircon is important in the refractory industry (Jones, 2009). REE are used as catalysts in the chemical industry, and in glass, re-chargeable batteries, magnets, lasers, TV color phosphors, solar panels, and wind turbines. Only India is currently mining monazite from modern beach-placer sandstones for REE (Kramer-Miller, 2015).

As the demand for some of these commodities increases due to increase in prices and short supplies, the dollar value per ton of ore rises, enhancing deposit economics. Detailed mapping and exploration drilling of these deposits are essential to fully evaluate their economic potential (Bingler, 1968; Segerstrom and Henkes, 1977). Therefore the Jicarilla Apache Nation decided to examine the Apache Mesa deposits, previously discovered by the U.S. Atomic Energy Commission in 1956, to determine if they could be economic now or in the future (McLemore et al., 2016).

The purposes of this paper are to: 1) summarize the geologic setting of the beach-placer sandstone deposits at Apache Mesa and their stratigraphic context in the Point Lookout Formation, 2) describe the mineralogy and chemistry of these beach-placer deposits, and 3) summarize the economic mineral potential of the Apache Mesa deposits. This paper is a summary of a larger report, which gives more details on the geologic mapping and drilling used to determine the economic viability of these deposits (McLemore et al., 2016).

HISTORY AND PREVIOUS WORK

Most of the Cretaceous heavy mineral, beach-placer sandstone deposits in New Mexico, including the deposit at Apache Mesa, were discovered during airborne gamma-ray radiometric surveys in the 1950s by the U.S. Atomic Energy Commission while exploring for uranium (Murphy, 1956; Chenoweth, 1957). The airborne anomalies were subsequently verified by field examinations (Chenoweth, 1957; McLemore, 1983).

Nearshore facies in Late Cretaceous transgressive-regressive sequences throughout the Rocky Mountain region locally host similar beach-placer sandstone deposits, as stated above. Murphy (1956) described some of the deposits in the U.S. and recommended additional investigation. The stratigraphic, physical, and chemical attributes of beach-placer deposits in the San Juan Basin are summarized by Chenoweth (1957), Overstreet (1967), and McLemore (2010); the depositional environment of these deposits is described by Houston and Murphy (1970, 1977). Noteworthy localities in the San Juan Basin include the Sanostee beach-placer deposit (Bingler, 1963) and the deposits on the Ute Indian Reservation (Zech et al., 1994). McLemore et al. (1988a, b) and McLemore (2015) discussed the REE potential of beach-placer sandstone deposits in New Mexico.

The deposits at Apache Mesa were originally named the Stinking Lake deposits after a nearby lake by William Chenoweth (Chenoweth, 1957). Bingler (1968) also described these deposits. The name of the deposits was changed from Stinking Lake to Apache Mesa at the request of some Tribal members (McLemore et al., 2016).

METHODS

The Apache Mesa area was mapped according to standard geologic mapping techniques (Lahee, 1961; Carpenter and Keane, 2016) at a scale of 1:6,000 scale (McLemore et al., 2016). Drilling began on August 18, 2015 and was completed on August 25, 2015 (Table 1); drill logs are in McLemore et al. (2016). Mineralized samples were collected at the surface and from the drill core. Surface and core samples were dried, crushed, split and pulverized according to standard ALS Laboratory Group preparation methods PREP-31 (ALS, 2017). Samples were analyzed by ALS Laboratory Group for major and trace elements by a variety of analytical methods (CCP-PKG03 and Au-ICP21; ALS, 2017), including X-Ray Fluorescence (XRF), inductively coupled plasma atomic emission spectroscopy (ICP-AES), and inductively coupled plasma mass spectrometry (ICP-MS). Chemical analyses are in Appendix 1 (located at *http://nmgs.nmt.edu/repository/index.cfml?rid=201700X*) and McLemore et al. (2016).

Samples of beach-placer sandstones were examined using a Cameca SX100 electron microprobe to characterize their mineralogic and chemical composition as well as texture. This microprobe is housed at the New Mexico Institute of Mining and Technology (Electron Microprobe Laboratory, 2017). More details on the methodology and results are in McLemore et al. (2016).

Specific gravity of ores is an important parameter that is often under characterized in the determination of grade and tonnage of deposits. Specific gravity is determined by weighing a sample in air and in water, and it is reported as a ratio between the density of the sample and the density of water. Specific gravity measurements are in McLeore et al. (2016).

Unlike most types of deposits, mineral sands are generally reported in terms of percentage of minerals, specifically percent ilmenite, rutile, zircon, and so forth (Tables 2 and 3; Kattaa, 2002; Jones and O'Brien, 2014). However, there was not enough funding or time to determine quantitative mineral composition, so the chemical analyses were used to calculate ore reserves for this report. TiO_2 is a proxy for the amount of ilmenite, rutile, and leucoxene. Zr is a proxy for the amount of zircon. Total REE (TREE) is a proxy for the amount of monazite.

Since the Apache Mesa deposits are small and nearly flat lying, the classical polygon method of calculating ore reserves was used, which is a method of estimating ore reserves where it is assumed that each drill hole or sample has an area of influence extending approximately halfway to the neighboring drill hole or sample location (Popoff, 1966). The required data are summarized in Table 4 and details are in McLemore et al. (2016).

GEOLOGY OF APACHE MESA

Point Lookout Sandstone

Regional Characteristics

The Point Lookout Sandstone forms cliffs, caps mesas, or underlies dip slopes and hogbacks around the margins of the San Juan and Paradox Basins. The bulk of this variably thick formation was deposited along a falling shoreline (regressing to the east and north) of the Western Interior Seaway from 85.5-80.5 Ma (Molenaar et al., 2002). South of Apache Mesa, the lower part of the Point Lookout Sandstone has a transgressive unit represented by the Hosta Tongue (Fig. 3; Hollenshead and Pritchard, 1961; Tabet and Frost, 1979; Craigg et al., 1990; Devine, 1991; Zech et al., 1994). At Apache Mesa, the Point Lookout Sandstone conformably overlies the Mancos Shale and underlies the Menefee Formation (Fig. 3). Beach-placer deposits of the Point Lookout Sandstone are generally restricted to the uppermost part and are associated with upper shoreface, foreshore (swash zone), washover, and eolian environments (Landis at al., 1974; Fassett, 1977, 2000; Zech, 1982; Zech et al., 1994). The upper Point Lookout Sandstone also includes deltaic sandstones and lower shoreface facies, some of which are found along the northern rim of Apache Mesa.

Local Characteristics

At Apache Mesa, the Point Lookout Sandstone is 30.4–45.7 m (100–150 ft) thick and forms impressive cliffs (Figs. 4, 5, 6) (McLemore et al., 2016). The older, underlying Mancos Shale typically forms slopes covered by talus deposits eroded from the Point Lookout cliffs. Much of the top of Apache Mesa is forested and the exposures are mostly poor with only a few well-exposed outcrops.

Three distinct, informal units within the Point Lookout Sandstone are mapped at Apache Mesa (Figs. 4, 5, 6), listed

TABLE 1. Completed drill locations, Apache Mesa REE project. UTM coordinates are in NAD27, zone 13 and represent final drill hole locations. Drill holes are located in Figure 4 and final drilling report with graphic logs is in McLemore et al. (2016).

Final Drill Hole Id	UTM easting	UTM northing	Total depth (ft)	Completion	Purpose	Summary of goals
DH1	337543	4059240	112.3	8/19/2015	Confirmation to determine thickness of middle deposit	Deposit is 1.8 ft thick, Point Lookout Sandstone is 107 ft
DH2	337479	4059136	42.4	8/20/2015	Confirmation to determine thickness of middle deposit	No black sandstone, depositional environment suggests an inlet
DH3	337486	4059021	45	8/20/2015	Confirmation to determine thickness of middle deposit	Deposit is 3.2 ft thick
DH4	337590	4059418	83	8/21/2015	Preliminary hole DH 105, exploration to determine northern extent of middle deposit	No black sandstone deposit, did encounter gray sandstone at 73.8-74.8 ft
DH5	337732	4059035	113	8/21/15	Preliminary hole DH4, confirmation to determine thickness of eastern deposit and thickness of Point Lookout	0.2 ft black sandstone, Point Lookout is 108.6 ft thick
DH6	337723	4059200	53	8/22/15	Preliminary hole DH5, confirmation to determine thickness of eastern deposit	Black sandstone is 1.8 ft thick
DH7	337714	4058862	43	8/22/15	New hole (on road), confirmation to determine thickness of eastern deposit	Black sandstone is 3.5 ft thick
DH8	337733	4059310	53	8/22/15	Confirmation to determine thickness of eastern deposit	Black sandstone is 3.2 ft thick (loss recovery)
DH9	337749	4059465	53	8/22/15	Preliminary DH106, exploration to determine northern extent of eastern deposit	Black sandstone is 3.5 ft thick
DH10	338405	4059065	148	8/23/15	Preliminary hole DH109, wildcat to determine eastern extent, low priority	No black sandstone encountered, drilled through a white beach sandstone at base (either lower Point Lookout or another sandstone in the underlying shale), but no evidence of a black sandstone deposit
DH11	337840	4059780	48	8/24/15	Preliminary hole 111, exploration to determine northern extent	Black sandstone beneath coal
DH12	337369	4059715	27	8/24/15	Preliminary hole 103, exploration to determine northern extent	Encountered yellow sandstone, no black sandstone
DH13	337006	4059042	88	8/25/15	Preliminary hole 101, exploration	Point Lookout, if present here, is thin and underlain Mancos Shale, no black sandstone
DH14	337660	4059628	150	8/25/15	Preliminary hole 107, exploration	Encountered fault at 11.5 ft, most of hole in white, yellow and gray sandstone, no coal, no black sandstone

from bottom (oldest) to top (youngest): 1) yellow sandstone, 2) white sandstone, and 3) black sandstone. The yellow sandstone unit consists of yellow, massive to cross-laminated (low- to high-angle) sandstone. Sand grains are subangular to rounded, well to moderately sorted, and fine to medium grained (McLemore et al., 2016). The sand is composed of quartz, feldspar, and hematite, with a few lithic fragments and trace amounts of heavy, black minerals. Silica and hematite constitute the cement. Some beds show evidence of bioturbation and burrows. The cross-stratified sandstone probably represents deposition on the upper shoreface, where there is strong influence by waves and longshore currents. Massive and bioturbated sandstone were likely deposited in deeper water (lower shoreface and the transition to the offshore zone in Fig. 1). Both environments are generally unfavorable for formation of beach-placer sandstone deposits (Van Gosen et al., 2014).

The middle unit consists of white to light gray to olive gray, massive to planar cross-bedded with local trough cross-stratification. The degree of cross-stratification is less than in the older yellow sandstone. The sand is subangular to rounded,

TABLE 2. Ore reserves for heavy mineral beach-placer sandstone deposits in the world. Iluka ore reserves are from Iluka (2014).

Area	Total deposit (metric tons)	Year	Ilmenite % ($FeTiO_3$)	Rutile % (TiO_2)	Leucoxene % ($(Fe,Mg,Mn,Ti)O_3$)	Zircon % ($ZrSiO_4$)
Apache Mesa, New Mexico	120,564	2016	<3	-	-	<1
Atlantic Seaboard (Iluka)	19,700,000	2014	60	-	-	18
Eucla Basin, Australia (Iluka)	114,600,000	2014	27	4	-	51
Perth Basin, Australia (Iluka)	313,300,000	2014	59	5	-	10
Murray Basin, Australia (Iluka)	12,000,000	2014	47	19	-	13
Grande Côte, Senegal, West Africa	1,915,000	2015	-	2.5	3.2	10.7

TABLE 3. Required data for calculating the value of a potential mineral deposit.

Required data	Description
Grade	The concentration of the mineral or commodity in the ore deposit
Area	Area of the ore deposit (strike length and width)
Thickness	Thickness of the ore deposit
Specific gravity	The density of the ore deposit

TABLE 4. Ore reserves for the Apache Mesa heavy mineral, beach-placer sandstone deposit, New Mexico (McLemore et al., 2016). TiO_2 is a proxy for the amount of ilmenite, rutile, and leucoxene. Zr is a proxy for the amount of zircon. TREE is a proxy for the amount of monazite.

Area	Total	Total deposit (metric tons)	TiO_2	Cr	Nb	Zr	Th	TREE
Apache Mesa, NM	Metric tons	120,564	303,723	1,299	558	26,365	485	6,296
Apache Mesa, NM	Grade		3%	108 ppm	46 ppm	2,187 ppm	40 ppm	522 ppm

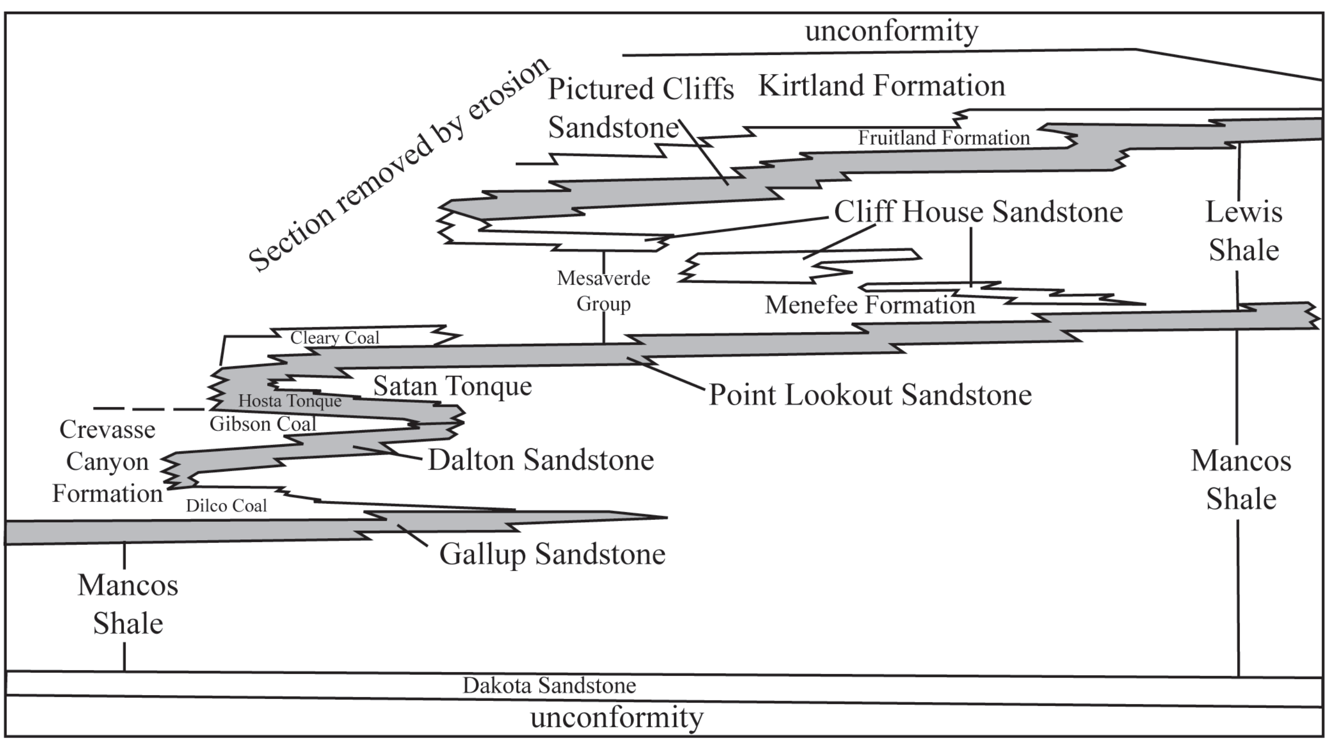


FIGURE 3. Stratigraphic framework and nomenclature of the Late Cretaceous sedimentary rocks in the San Juan Basin (simplified from Molenaar, 1989; Craigg et al., 1990). Gray-shaded sandstone units are hosts of known beach-placer sandstone deposits in the San Juan Basin.

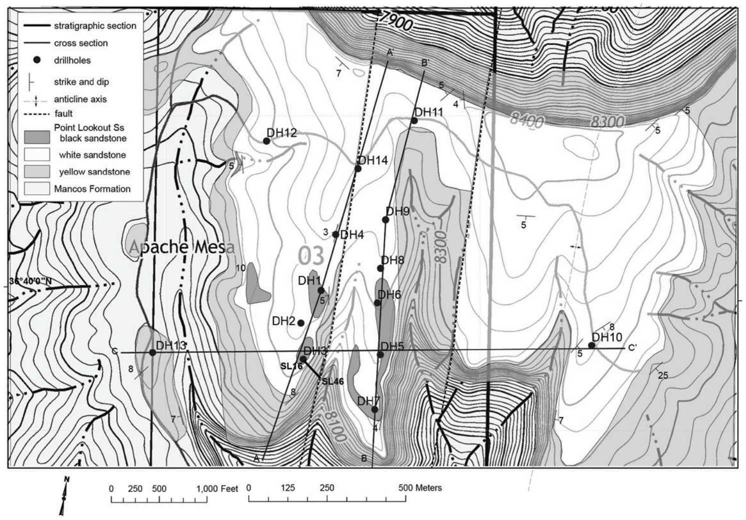


FIGURE 4. Geologic map of the Apache Mesa area, Rio Arriba County, New Mexico. Cross sections are below and shown in McLemore et al. (2016).

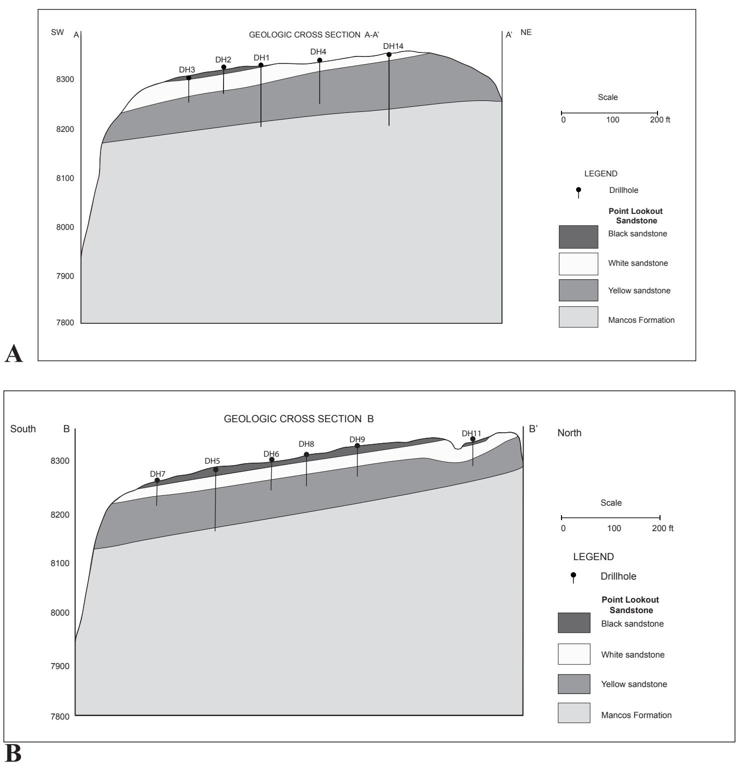
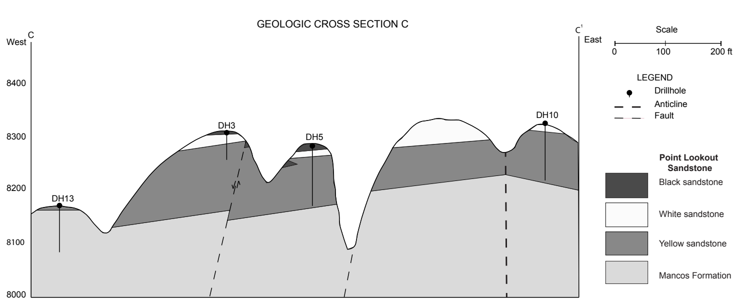


FIGURE 5. **A.** and **B.** North-south cross sections (A–A', B–B') across Apache Mesa (see McLemore et al., 2016). Locations of cross sections are in Figure 4.



medium to fine grained, and moderately to well sorted. The sand is composed of quartz and feldspar, with few lithic fragments and trace heavy, black minerals. The cementing agent is silica. Similar to the older sandstone, this unit is interpreted to have been deposited in the upper shoreface and possibly (for the massive sandstones) the transition between the lower shoreface-to-offshore zone (Fig. 1). These environments generally underlie the beach-placer sandstones and are unfavorable in preserving beach-placer deposits (van Gosen et al., 2014). However, unrecognized thin foreshore deposits may be present in this unit or the underlying yellow sandstone given the sequence stratigraphic framework and sedimentologic observations interpreted by previous workers (e.g., Devine, 1991; Katzman and Dunbar-Wright, 2002).

Capping the stratigraphic sequence in most of the western portion of Apache Mesa, the black sandstone unit is lense-shaped, less than 0.3–3 m (1–9.9 ft) thick, and thins to the north and west. It is not exposed or preserved on the eastern mesa nor along the cliff on the northern edge (Figs. 4, 6). The black sandstone is reddish-purple to olive-brown to grayish red to black red, moderately to well cemented, and mostly medium grained. This unit is massive or planar-bedded, where beds consist of alternating layers of millimeter to centimeter thick, gray and red to dusky red sandstone. The sand contains quartz, feldspar, and abundant iron oxide minerals, leucoxene, zircon, tourmaline, rutile, magnetite, monazite, chromite, ilmenite, and trace gold. The planar bedding is consistent with deposition along the foreshore of a beach or in a washover fan (periodically subjected to bioturbation that produced massive bed forms). Initial deposition may have occurred during high tide and/or storm surges, with subsequent back-and-forth currents winnowing the sand (Fig. 1).

Along the northern rim of Apache Mesa (near DH11, Fig. 4), the uppermost Point Lookout Sandstone consists of 1-3 m of thinly interbedded brown carbonaceous shale, black coal to humates, and white to yellow siltstones to fine-grained sandstones that overlie the white sandstone, which exhibits large high-angle to trough cross-stratification (McLemore et al., 2016). This cross-stratification could be related to a river or tidal inlet (Katzman and Dunbar-Wright, 1992). In DH11, coal overlies a thin black sandstone bed (McLemore et al., 2016). These particular strata are interpreted to have been deposited in a general backshore environment (which might include coastal bay, swamp, lagoon, and fluvial environments). A backshore environment is generally unfavorable for formation of beach-placer sandstone deposits except seaward near barrier islands,

FIGURE 6. East–west cross section across Apache Mesa (C–C'; see McLemore et al., 2016). Locations of cross sections are in Figure 4.

where washover and tidal deltas may be present. These younger units probably represent the upper portion of the Point Lookout Sandstone as described by Landis et al. (1974) and were mapped in this paper as part of the white sandstone unit of the Point Lookout Sandstone at Apache Mesa.

The older Mancos Shale is approximately 609.6 m (2000 ft) thick in the region and is generally poorly exposed. At Apache Mesa the Mancos Shale is exposed along the western ridge and beneath Apache Mesa (Figs. 4, 5, 6). The upper Mancos Shale consists of gray to dark gray, thinly bedded, lenticular to tabular shale interbedded with gray and yellow, thinly bedded, carbonate-cemented, fine- to very fine-grained sandstone, silty sandstone, and siltstone. The sandstones exhibit small scale, tabular to hummocky, cross laminations with local ripple beds and bioturdation. Locally, thin beds of coal are interbedded with the shale. These upper strata were likely deposited in the transition between the lower shoreface and offshore environments.

Structure

Apache Mesa is formed in part by a north-trending anticline (Figs. 4, 5; McLemore et al., 2016), where the sedimentary rocks dip gently to the west or east. The rocks dip gently to the west on the west limb of the anticline and to the east on the east limb (Fig. 3). Apache Mesa also is cut by two steeply-dipping, north-trending faults, but the displacements along these faults are minor, less than 15.2 m (50 ft) (McLemore et al., 2016). The age of the folding and faulting is likely Eocene to late Miocene (Segerstrom and Henkes, 1977).

MINERALOGY AND CHEMISTRY OF THE APACHE MESA BEACH-PLACER SANDSTONE DEPOSIT

The majority of the black-sandstone samples are detrital and composed mostly of quartz, some lithic fragments, feldspar, and heavy minerals. Alteration and weathering of grains is apparent in these samples, although the intensity varies. Cementation is composed mostly of iron oxide and minor silica. Petrographic, chemistry, and electron microprobe results confirm the presence of iron oxides, ilmenite, rutile, zircon, monazite, xenotime, garnet, and illite in these beach-placer sandstone deposits (Figs. 7, 8; McLemore et al., 2016). The heavy mineral grains are oblong, rounded, and somewhat altered. The albite grains are blockier and less altered than the more rounded quartz. The zircon grains are very fractured and blocky. Some of the ilmenite grains are zoned and much of the ilmenite is either altered partially to hematite or is in solid solution series with hematite. A few grains of chromite, and one grain of gold with a silver-rich rim, also are found in the Apache Mesa deposits. Gold particles with silver-rich rims are common in placer gold deposits (Luterbach and McLemore, 2016).

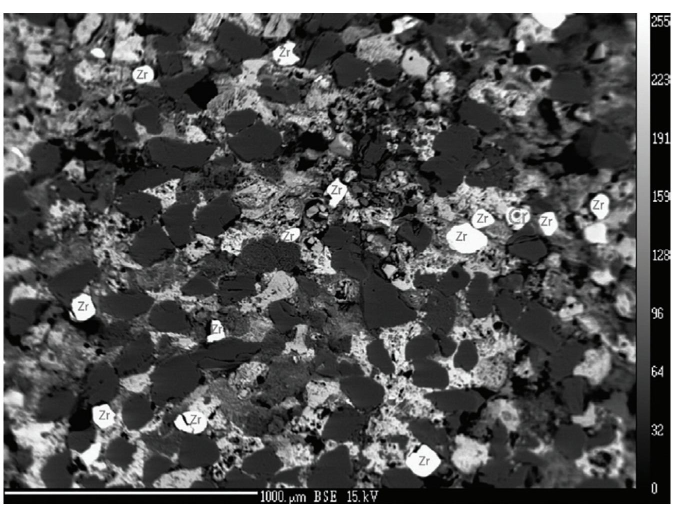


FIGURE 7. Electron microprobe backscatter image of sample SL 16 (Apache Mesa). Zircon grains are labeled in red (Zr). Chromite is labeled in blue (Cr). Mottled, lighter colored cement is iron oxide (hematite). Dark grains are mainly quartz. Photograph by A. Robison.

COMPARISON OF APACHE MESA WITH OTHER BEACH-PLACER SANDSTONE DEPOSITS

The proportion of various heavy elements in the chemical analyses compares well with those of other beach-placer sandstone deposits (Figs. 8, 9, 10; Appendix 1 at *http://nmgs.nmt.edu/repository/index.cfml?rid=201700X; Mc*Lemore et al., 2016). Locally high concentrations of Ti, Fe, Cr, Nb, Th, U, Zr, Sc, and REE are found in the Apache Mesa beach-placer sandstone deposits. The REE plots exhibit light-REE enriched chondrite-normalized patterns, typically with negative Eu anomalies (Fig. 8). TiO_2 and Zr as well as U and Th show a strong correlation (Figs. 9, 10), similar to trends in other beach-placer sandstones.

ORIGIN OF BEACH-PLACER SANDSTONE DEPOSITS

The Cretaceous heavy mineral, beach-placer sandstone deposits discussed herein share many physical and chemical characteristics to modern beach placers, including mineralogy, chemistry, and depositional environment (Houston and Murphy, 1970, 1977; Zech et al., 1994; Roy, 1999; Van Gosen et al., 2014). However, the Cretaceous deposits are moderately to well cemented, whereas the modern deposits are unconsolidated and can be ripped during mining with dozers without any blasting.

Beach-placer deposits form by gravitational settling of the heavy minerals during wave action and currents that form beaches and offshore sand bars (Fig. 1; Houston and Murphy, 1970, 1977; Zech et al., 1994; Roy, 1999). The waves carry off the lighter minerals leaving behind the heavy minerals. The deposits in eastern Australia were formed during low rates of clastic supply and long periods of weathering and abrasion of beach deposits (Roy, 1999). Transgressive and regressive shoreline movements, such as occurred in Late Cretaceous time in the San Juan Basin area, result in the formation of extensive shoreface-sandstone deposits covering thousands of square miles. Once the shoreface sandstone deposits are deposited they are covered by continental facies, which preserve them unless later erosion exposes them. The heavy minerals tend to concentrate in the upper 30.5 m (100 ft) of the beach, decreasing in concen-

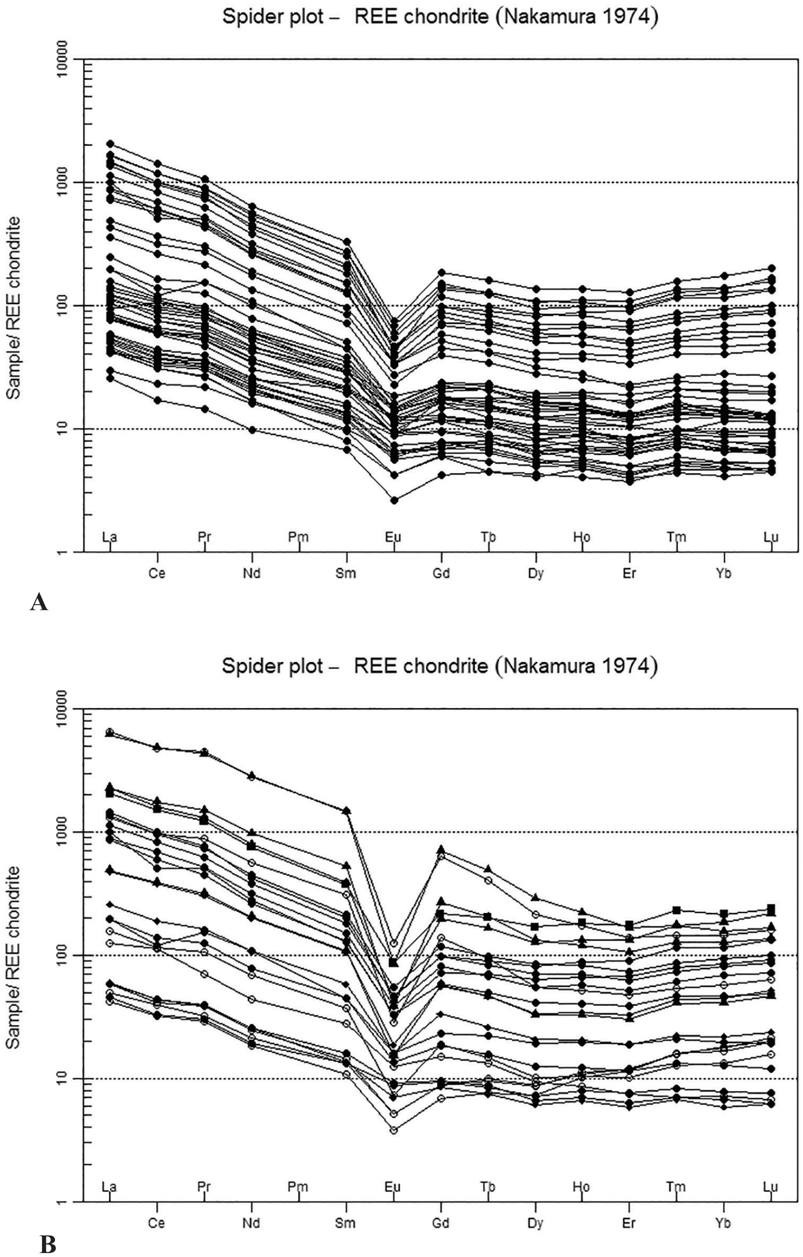


FIGURE 8. Chondrite-normalized REE plot (Nakamura, 1974) of selected heavy mineral, beach-placer deposits: **A.** Apache Mesa (circles); **B.** shows trends for Standing Rock (diamond), Sanostee (triangle), and B.P. Hovey (square), San Juan Basin, New Mexico and Virginia (open circles). All chemical analyses are in McLemore et al. (2016) and Appendix 1.

tration seaward. In the seaward region, the undertow removed the finer and lighter minerals, whereas in the landward region, wind transported the finer or lighter minerals away. Riptides and undertow currents erode beach deposits and subsequently remove the lighter minerals, leaving the heavier minerals behind. Destruction and reworking of older beach-placer deposits can occur until they are covered by continental deposits.

MINERAL-RESOURCE POTENTIAL

The ore reserves at Apache Mesa are summarized in Table 4; details are in McLemore et al. (2016). These estimates are much lower than ore reserves reported for other deposits along the Atlantic Coast, Australia, and Africa (Table 2). Economic heavy mineral, beach-placer sandstone deposits are typically greater than 10 million short tons of greater than 2% heavy minerals and are mined by open-pit methods where any topsoil is removed and stockpiled (Van Gosen et al., 2014). Gravity spirals are used to separate the denser heavy minerals, then electrostatic and magnetic separators separate the individual heavy mineral constituents; the mineral concentrates are then sold.

CONCLUSIONS

At Apache Mesa, Cretaceous beach-placer sandstone deposits are found in reddish-purple to olive-brown to grayish red to black red, moderately- to well-sorted, moderately- to well-cemented, medium-grained sandstones that contains abundant iron oxide minerals, leucoxene, zircon, tourmaline, rutile, magnetite, monazite, chromite, ilmenite, and trace gold. It overlies a white, light gray to olive gray, massive to planar cross-bedded, medium- to fine-grained, moderately- to well-sorted sandstone, locally with trough cross-stratification. These units are interpreted to have been deposited in the beach environment.

The Apache Mesa heavy mineral, beach-placer sandstone deposits are similar in appearance, texture, mineralogy, chemical composition, specific gravity, and origin to beach-placer sandstone deposits elsewhere in the San Juan Basin and in Virginia, although the Virginia deposits are much thicker, unconsolidated, and have a lower specific gravity (McLemore et al., 2016). The Cretaceous beach-placer sandstone deposits are more cemented and smaller in size than the younger heavy mineral, beach-placer sandstone deposits found in Virginia, Australia, and India, which increases mining costs. Although, some individual analyses of samples from Apache Mesa contain high concentrations of TiO_2 (15%), Cr (590 ppm), Nb (260 ppm), Zr (>10,000 ppm), Th (258 ppm), and total REE (2,692 ppm); the Apache Mesa beach-placer sandstone deposit is overall much smaller, thinner and lower in trace element constituents (Appendix 1 at *http://nmgs.nmt.edu/repository/index.cfml?rid=201700X*). The Apache Mesa beach-placer sandstone deposits contain only 132,900 short tons (120,564 metric tons) of ore with grades of 3% TiO_2, 108 ppm Cr, 46 ppm Nb, 2,187 ppm Zr, 40 ppm Th, and 522 ppm total REE. In conclusion, the Apache Mesa heavy mineral, beach-placer sandstone deposit is too small and low grade to be economic in today's market. No further investigation is recommended at this time.

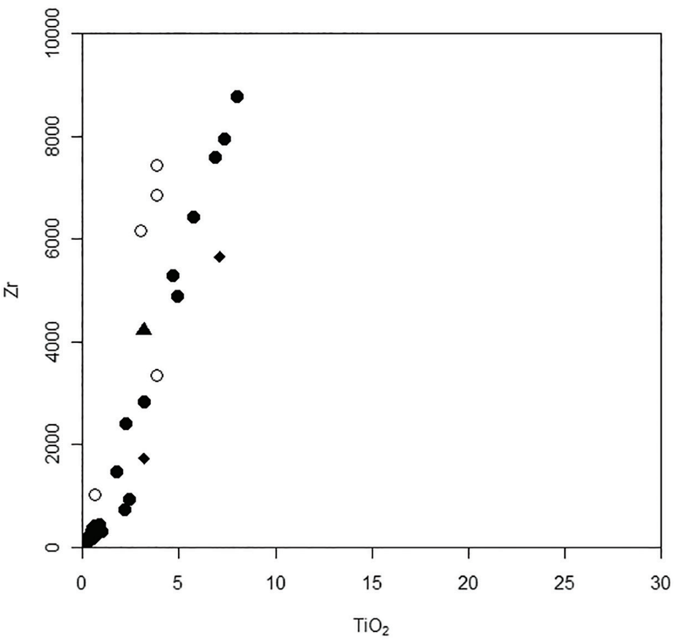


FIGURE 9. Zr-TiO_2 plot of selected heavy mineral, beach-placer deposits, Apache Mesa (circles), Standing Rock (diamonds), Sanostee (triangles), and B.P. Hovey (squares), San Juan Basin, New Mexico and Virginia (open circles). All chemical analyses are in McLemore et al. (2016) and Appendix 1.

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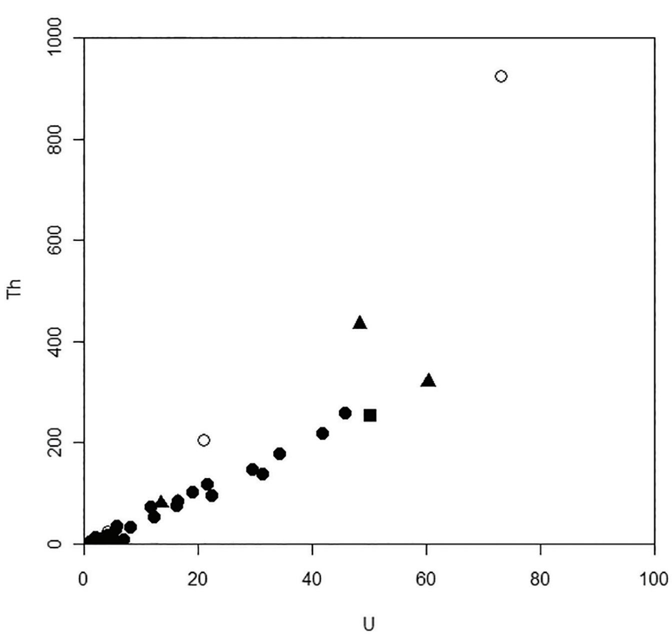

FIGURE 10. U-Th plot of selected heavy mineral, beach-placer deposits, Apache Mesa (circles), Standing Rock (diamonds), Sanostee (triangles), and B.P. Hovey (squares), San Juan Basin, New Mexico and Virginia (open circles). All chemical analyses are in McLemore et al. (2016) and Appendix 1.

REFERENCES

Allen, J.E., 1956, Titaniferous Cretaceous beach placer in McKinley County (abstr.): Geological Society of America Bulletin, v. 67, p. 1789.

ALS, 2017, 2017 Geochemistry schedule of services and fees USD: https://www.alsglobal.com/myals/downloads?keywords=Fee+Schedule&category=b5b5208b58bc4609bd2fa20f32d820f8 (accessed May 12, 2017).

Bingler, E.C., 1963, Niobium-bearing Sanostee heavy mineral deposit, San Juan Basin, northwestern New Mexico: New Mexico Bureau Mines Mineral Resources, Circular 68, 63 p.

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.

Brookins, D.G., 1977, Upper Cretaceous black sand deposits of the San Juan Basin: New Mexico Geological Society, Guidebook 28, p. 31–33.

Bryan, K.R., Robinson, A., and Briggs, R.M., 2007, Spatial and temporal variability of titanomagnetite placer deposits on a predominantly black sand beach: Marine Geology, v. 236, p. 45–59.

Carpenter, M.B., and Keane, C.M., 2016, The geoscience handbook 2016: Alexandria, Virginia, American Geosciences Institute (AGI) Data Sheets, 5th edition, 480 p.

Carpenter, R.H., and Carpenter, S.F., 1991, Heavy mineral deposits in the upper coastal plain of North Carolina and Virginia: Economic Geology, v. 86, p. 1657–1671.

Chenoweth, W.L., 1957, Radioactive titaniferous heavy mineral deposits in the San Juan Basin, New Mexico and Colorado: New Mexico Geological Society, Guidebook 8, p. 212–217.

Craigg, S.D., Dam, W.L., Kernodle, J.M., Thorn, C.R., and Levings, G.W., 1990, Hydrogeology of the Point Lookout Sandstone in the San Juan structural basin, New Mexico, Colorado, Arizona, and Utah: U.S. Geological Survey, Hydrologic Investigations Atlas HA-720-G, 2 sheets.

Devine, P.E., 1991, Transgressive origin of channeled estuarine deposits in the Point Lookout Sandstone, northwestern New Mexico—A model for Upper Cretaceous, cyclic regressive parasequences of the U.S. western interior: American Association of Petroleum Geologists, Bulletin, v. 75, p. 1039–1063.

Dow, V.T., and Batty, J.V., 1961, Reconnaissance of titaniferous sandstone deposits of Utah, Wyoming, New Mexico and Colorado: U.S. Bureau of Mines, Report of Investigations RI-5860, 52 p.

Electron Microprobe Laboratory, 2017, https://geoinfo.nmt.edu/labs/microprobe/home.html (accessed May 2, 2017).

Fassett, J.E., 1977, Geology of the Point Lookout, Cliff House and Pictured Cliffs Sandstones of the San Juan Basin, New Mexico and Colorado: New Mexico Geological Society, Guidebook 28, p. 193–197.

Fassett, J.E., 2000, Geology and coal resources of the Upper Cretaceous Fruitland Formation, San Juan Basin, New Mexico and Colorado, *in* Kirschbaum, M.A., Roberts, L.N.R., and Biewick, L.R.H., eds., Geologic assessment of coal in the Colorado Plateau; Arizona, Colorado, New Mexico, and Utah: U.S. Geological Survey Professional Paper 1625-B, Q1–Q132.

Force, E.R., 1991, Geology of titanium-mineral deposits: Geological Society of America Special Paper 259, 112 p.

Force, E.R., 2000, Titanium mineral resources of the western U.S—an update: U.S. Geological Survey, Open-file Report 00–442, 43 p.

Hollenshead, C.T., and Pritchard, R.L., 1961, Geometry of producing Mesaverde sandstone of the San Juan Basin; in Geometry of sandstone bodies: Association of Petroleum Geologists, symposium volume, p. 68–118, http://archives.datapages.com/data/bulletns/1957-60/images/pg/00440007/1250/12500.pdf, accessed May 2, 2017.

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, p. 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 p. A1–A29.

Iluka, 2014, Ore Reserves and Mineral Resources Statement: Iluka Annual Report, http://www.iluka.com/docs/default-source/3.2-ore-reserves-mineral-resources/annual-statement-of-reserves-and-resources2014.pdf?sfvrsn=4 (accessed May 2, 2017).

Jones, G., 2009, Mineral sands—an overview of the industry: Perth, WA, 7th International Mining Geology Conference, p. 213–222.

Jones, G., and O'Brien, V., 2014, Aspects of resource estimation for mineral sands deposits: Aspects of resource estimation for mineral sands deposits: Applied Earth Science, v. 123, no. 2, 86-94.

Kattaa, B., 2002, Heavy mineral survey of the Syrian beach sands, south of Tartous: their nature, distribution and potential: Exploration Mining Geology, v. 11, p. 31–41.

Katzman, D.R. and Wright-Dunbar, R., 1992, Parasequence geometry and facies architecture in the upper Cretaceous Point Lookout Sandstone, Four Corners platform, southwestern Colorado: New Mexico Geological Society, Guidebook 43, p. 187-197.

Koch, G.S., 1986, A geochemical atlas of Georgia: Georgia Geologic Survey, Geological Atlas No. 3, 44 p.

Kramer-Miller, 2015, The big rare eath story that no one is talking about: https://seekingalpha.com/article/3585086-big-rare-earth-story-one-talking (accessed on May 2, 2017).

Lahee, F.H., 1961, Field geology: McGraw-Hill Book Company, New York, 926 p.

Landis, E.R., Dane, C.H., and Cobban, W.A., 1974, Cretaceous rocks of the Tierra Amarilla coal field and adjacent areas, Rio Arriba County, New Mexico: New Mexico Geological Society, Guidebook 25, p. 231–238.

Luterbach, T., and McLemore, V.T., 2016, Trace element analysis of placer gold samples: Society for Mining, Metallurgy, and Exploration, 2016 Annual meeting preprint 16-062, 4 p., http://geoinfo.nmt.edu/staff/mclemore/projects/documents/16_062.pdf (accessed 5/1/2016).

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 p.

McLemore, V.T., 1983, Uranium and thorium occurrences in New Mexico—distribution, geology, production, and resources; with selected bibliography: New Mexico Bureau of Mines and Mineral Resources, Open file Report 182, 950 p., also; U.S. Department of Energy Report GJBX-11 (83).

McLemore, V.T., 2010, 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, p. 197–212.

McLemore, V.T., 2011, Rare earth elements for emerging technologies: New Mexico Earth Matters, summer, 4 p., http://geoinfo.nmt.edu/publications/periodicals/earthmatters/11/EM11n2.pdf (accessed 5/1/2016).

McLemore, V.T., 2015, Rare Earth Elements (REE) deposits in New Mexico: Update: New Mexico Geology, v. 37, p. 59–69, http://geoinfo.nmt.edu/publications/periodicals/nmg/current/home.cfml (accessed 5/1/2016).

McLemore, V.T., Asafo-Akowuah, J., and Robison, A., 2016, Assessment of rare earth elements at Apache Mesa (Stinking Lake), Jicarilla Apache Reservation, Rio Arriba County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file report 587, http://geoinfo.nmt.edu/publications/openfile/details.cfml?Volume=587 (accessed May 2, 2017.

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 p.

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

McLemore, V.T., and Robison, A., 2016, Exploration of beach-placer heavy mineral deposits in the San Juan Basin in New Mexico: Society for Mining, Metallurgy, and Exploration, 2016 Annual meeting Preprint 16–136, 10 p., http://geoinfo.nmt.edu/staff/mclemore/projects/documents/16_136.pdf (accessed 5/1/2016).

Molenaar, C.M., 1989, San Juan Basin stratigraphic correlation chart, in W.I. Finch, A.C. Huffman, Jr., and J.E. Fassett, eds., Coal, uranium, and oil and gas in Mesozoic rocks of the San Juan Basin—Anatomy of a giant energy-rich basin: 28th International Geological Congress, Washington, D.C., Guidebook for Field Trip T120, p. xi.

Molenaar, C.M., Cobban, W.A., Merewether, E.A., Pillmore, C.L., Wolfe, D.G., and Holbrook, J.M., 2002, Regional stratigraphic cross sections of Cretaceous rocks from east-central Arizona to the Oklahoma Panhandle: U.S. Geological Survey, Miscellaneous Field Studies Map 2382, 3 sheets.

Morteani, G., 1991, The rare earths: their minerals, production and technical use: European Journal of Mineralogy, v. 3, p. 641–650.

Murphy, J.F., 1956, Preliminary report on titanium-bearing sandstones in the San Juan Basin and adjacent areas in Arizona, Colorado, and New Mexico: U.S. Geological Survey, Open-file Report 56-0086, 8 p.

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

Overstreet, W.C., 1967, The geologic occurrence of monazite: U.S. Geological Survey, Professional Paper 530, 327 p.

Peterson, C.D., Komar, P.D., and Scheidegger, K.F., 1986, Distribution, geometry, and origin of heavy mineral placer deposits on Oregon beaches: Journal of Sedimentary Petrology, v. 56, p. 67–77.

Philander, C., and Rozendall, A., 2015, Geology of the Cenozoic Namakwa Sands heavy mineral deposit, west coast of South Africa: world-class resource of titanium and zircon: Economic Geology, v. 110, p. 1577–1623.

Pirkle, F.L., Pirkle, W.A., and Pirkle, E.C., 2009, Heavy mineral sands of the Atlantic and Gulf coastal plains, USA; Developments in Sedimentology, v. 58, p. 1145–1232.

Popoff, C.C., 1966, Computing reserves of mineral deposits: Principles and conventional methods: U.S. Bureau of Mines, Information Circular 8283, 122 p.

Rao, M.J., Raj, A. A.J., and Paul, K.J., 2008, Occurrence of zincian ilmenite from Srikurmam placer sand deposit, Andhra Pradesh, India: Current Science, vol. 95, no. 9, 10, p. 1124–1127.

Reid, A., Keeling, J., Boyd, D., Belousova, E., and Hou, B., 2013, Source of zircon in world-class heavy mineral placer deposits of the Cenozoic Basin, southern Australia from LA-ICPMS U-Pb geochronology: Sedimentary Geology, v. 286–287, p. 1–19.

Roy, P.S., 1999, Heavy mineral beach placers in southeastern Australia: Their nature and genesis: Economic Geology, v. 94, p. 567–588.

Segerstrom, K., and Henkes, W.C., 1977, Status of mineral resource information for the Jicarilla Indian Reservation, New Mexico: U.S. Geological Survey, Adminstrative Report BIA-25, 22 p.

Shelby, C.A., 1965, Heavy Minerals in the Wellborn Formation, Lee and Burleson Counties, Texas: Texas Bureau of Economic Geology, Report of Investigation 55, 55 p.

Tabet, D.E., and Frost, S.J., 1979, Coal geology of Torreon Wash area, southeast San Juan Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 49, 3 sheets, scale 1:24,000.

Van Gosen, B.S., Fey, D.L., Shah, A.K., Verplanck, P.L., and Hoefen, T.M., 2014, Deposit model for heavy mineral sands in coastal environments: U.S. Geological Survey Scientific Investigations Report 2010–5070–L, 51 p.

Zech, R.S., 1982, Paleoshorelines in the Upper Cretaceous Point Lookout Sandstone, southern San Juan basin, New Mexico: U.S. Geological Survey, Open-file report 82–135, 25 p.

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 p.

Supplemental data can be found at http://nmgs.nmt.edu/repository/index.cfml?rid=2017006