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

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SUMMARY

Several 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 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, India, where they are mined for titanium, zircon, and locally, monazite (a Ce-bearing rare earth elements, REE, mineral). Other potential commodities include niobium, chromium, thorium, and rare earth elements (REE). The Apache Mesa beach-placer sandstone deposit is similar in origin, texture, mineralogy, and chemical composition to beach-placer sandstone deposits elsewhere in the San Juan Basin and in the world. Although, some individual analyses of samples from Apache Mesa contained high concentrations of TiO_2 (15%), Cr (590 ppm), Nb (260 ppm), Zr (10,000 ppm), Th (258 ppm), and TREE (2,692 ppm); 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 TREE. 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.

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INTRODUCTION

Several Cretaceous heavy mineral, beach-placer sandstone deposits are found in the Point Lookout Sandstone on the Jicarilla Apache Reservation in Rio Arriba County. 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 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). Modern examples 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, Syria (Kattaa, 2002), and Andhra Pradesh, India (Rao et al., 2008), where they 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). Detrital heavy minerals comprise approximately 50–60% of these sandstones and typically consist of titanite, zircon, magnetite, ilmenite, monazite, apatite, rutile, xenotime, garnet, and allanite, among other heavy minerals. Most of these minerals have a high specific gravity exceeding 4 and are dark colored, giving the sandstones a dark color, resulting in them also being called black sandstones. 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; McLemore and Robinson, 2016). The beach-placer sandstones in New Mexico are black, dark gray, to olive-brown, resistant to erosion, and radioactive due to radioactive zircon, monazite, apatite, and thorium minerals. Anomalously high concentrations of titanium, iron, niobium, thorium, uranium, zirconium, scandium, yttrium, and REE are characteristic 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).

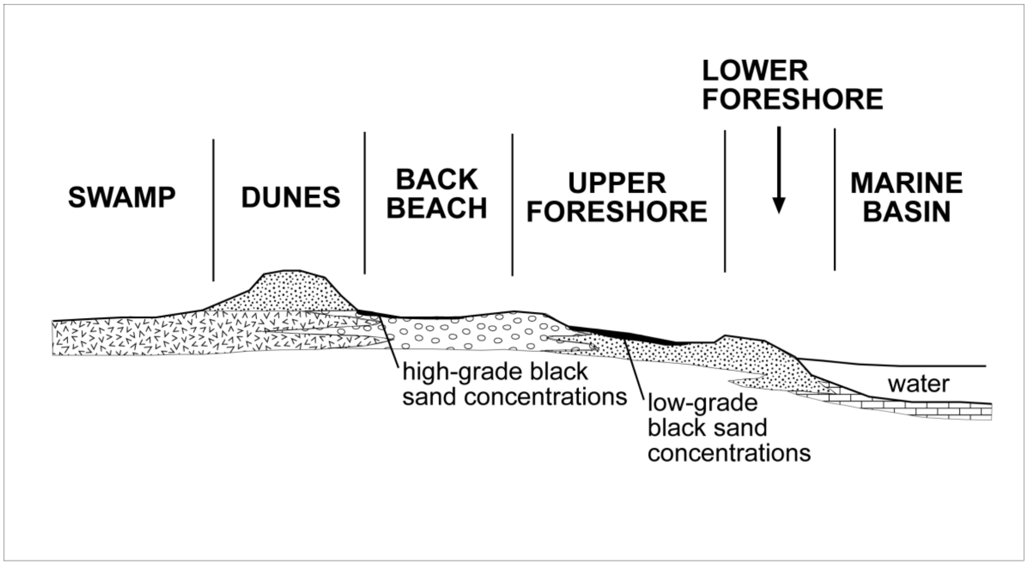


FIGURE 1. Idealized cross-section of formation of heavy mineral, beach-placer sandstone deposits (Houston and Murphy, 1970, 1977).

The mineral sands industry refers to deposits containing concentrations of heavy minerals in alluvial (beach or river system) or aeolian (dune sands) environments and consists of two important products: titanium minerals (rutile, ilmenite, leucoxene) and zircon (Jones, 2009; Pirkle et al., 2009). Other heavy minerals are found in many mineral sands that can be economic (Table 1; such as monazite, garnet, staurolite, kyanite) and are mined locally. Only India is currently mining monazite for REE (http://seekingalpha.com/article/3585086-big-rare-earth-story-one-talking, accessed 6/1/2016).

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, such as cell phones, computer monitors, televisions, solar panels, wind turbines, etc. (Table 1; Morteani, 1991; Long et al., 2010; McLemore, 2011). Titanium is a major component of pigment, glazes, and light-weight metal alloys (Force, 1991, 2000; Jones, 2009). Titanium in pigment is an important ingredient in paint, plastics, and paper, not only for its white color but also because it has a high refractive index. Titanium metal has a high strength to weight ratio and is resistant to corrosion. Zircon is important in the refractory industry (Jones, 2009).

REE include the 15 lanthanide elements (atomic number 57–71), yttrium (Y, atomic number 39), and scandium (Sc) and are commonly divided into two chemical groups, the light

REE (La through Eu) and the heavy REE (Gd through Lu and Y). REE are lithophile elements (or elements enriched in the crust) that have similar physical and chemical properties, and, therefore, occur together in nature. The United States once produced enough REE for United States consumption, but since 1999 more than 90% of the REE required by United States industry have been imported from China. However, the projected increase in demand for REE in China, Japan, India, United States, Europe, and other countries could result in increased exploration and ultimate production from future deposits in the United States and elsewhere. Furthermore, specific REE are becoming more economically important, especially the heavy REE.

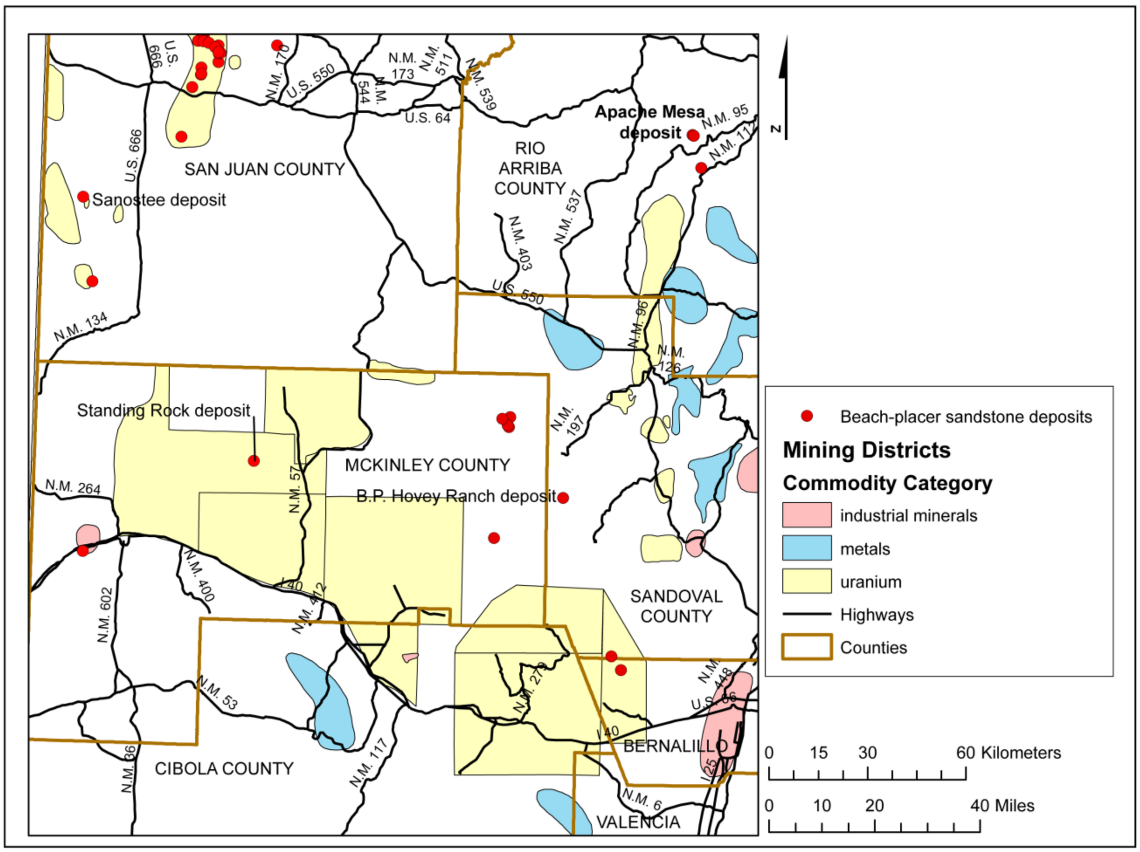


FIGURE 2. Location of Late Cretaceous heavy mineral, beach-placer sandstone deposits in the San Juan Basin, New Mexico. Deposits are described in McLemore (2010) and McLemore and Robinson (2016).

TABLE 1. Some uses of selected commodities found in Cretaceous heavy mineral, beach-placer sandstone deposits in New Mexico. Price is from U.S. Geological Survey (2016) for 2015. Na=not available

Commodity	Primary Mineral	Specific Gravity	Price ($/metric ton)	Selected Uses
Titanium	Rutile (TiO_2), leucoxene (TiO_2), ilmenite ($FeTiO_3$)	4.2–5.0	110 (ilmenite)-840 (rutile)	white pigment found in toothpaste, paint, paper, glazes, and some plastics, heat exchangers in desalination plants, alloys in aircraft, welding rods
Zirconium	Zircon ($ZrSiO_4$)	4.7	1050 (zircon)	ceramic tiles, bricks used to line steel making furnaces, mold and chill sands, alloying agent in steel, laboratory crucibles
Iron	Magnetite (Fe_3O_4)	5.2	na	additive in cement, iron ore, steel
REE	Monazite $(Ce,La,Y,Th)PO_4$	4.9–5.3	na	catalyst, glass, polishing, re-chargeable batteries, magnets, lasers, glass, TV color phosphors, solar panels, wind turbines
Niobium	Trace element in other minerals	na	na	used in alloys including stainless steel, superconducting magnets for particle accelerators, MRI scanners
Chromium	Chromite **(**$FeCr_2O_4$)	4.5–4.8	na	Stainless steel
Uranium	Monazite $(Ce,La,Y,Th)PO_4$	4.9–5.3	na	fuel for nuclear reactors to generate electricity, projectiles, shielding of radioactive materials
Thorium	Monazite $(Ce,La,Y,Th)PO_4$	4.9–5.3	na	fuel for thorium-reactors
Yttrium	Monazite $(Ce,La,Y,Th)PO_4$, xenotime YPO_4	4.9–5.3, 4.4–5.1	na	additive in alloys to increase strength, microwave filters, lasers, catalyst
Staurolite	Staurolite $(Fe, Mg, Zn)_2Al_6O_6(SiO_4)_4(O,OH)_2$	3.6–3.8	na	abrasive
Kyanite	Kyanite (Al_2SiO_5)	3.6–3.7	290	refractory products (bricks, mortars, kilns, molds), brake shoes, clutch facings, porcelain
Garnet	Garnet $(Fe,Mn,Ca)_3{\cdot}Al_2(SiO_4)_3$	3.4–4.2	na	abrasive

As the demand for some of these commodities increases due to increased price 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 Tribe decided to examine the Apache Mesa deposits to determine if they could be economic now or in the future.

Purpose

The purposes of this report are to: 1) describe the heavy mineral, beach-placer sandstone deposits at Apache Mesa, 2) summarize the formation, tectonic setting, stratigraphy, and origin of these deposits, 3) compare the Apache Mesa deposits to other known deposits in the San Juan Basin and economic deposits in Virginia and elsewhere, and 4) summarize the economic mineral potential of the Apache Mesa deposits. A glossary of terms is in Appendix 1.

History and previous work

Most of the Cretaceous heavy mineral, beach-placer sandstone deposits in New Mexico 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), and originally were simply identified as Airborne Anomaly Number 1, 2, and so forth. The airborne anomalies were subsequently verified by field examinations that are documented by a series of Preliminary Reconnaissance Reports (PRR; see McLemore, 1983). Similar beach-placer sandstone deposits are found in Late Cretaceous rocks throughout the Rocky Mountain region including Alberta (Canada), Montana, Wyoming, Colorado, Arizona, Utah, and northeastern Mexico (Houston and Murphy, 1970, 1977; Force, 1991, 2000). Murphy (1956) described some of the deposits in these states and recommended additional investigation. Chenoweth (1957), Dow and Batty (1961), Overstreet (1967), Brookins (1977), and McLemore (2010) summarized the stratigraphy and physical and chemical attributes of the deposits in the San Juan Basin. Bingler (1963) described the Sanostee beach-placer deposit and Bingler (1968) described the deposits at Apache Mesa (he named them Stinking Lake). Houston and Murphy (1970, 1977) described the depositional environment of the deposits. Zech et al. (1994) described the deposits on the Ute Indian Reservation and included detailed chemistry of most of these deposits (McLemore, 2010). McLemore et al. (1988a, b) and McLemore (2015) discussed the REE potential of beach-placer sandstone deposits in New Mexico.

PROPERTY DESCRIPTION

Location

The Apache Mesa deposits (also known as Airborne Anomalies 1–2, Stinking Lake) is in sections 2 and 3, T28N, R1E (Apache Mesa topographic quadrangle) on the Jicarilla Apache Reservation in the eastern San Juan Basin, northern New Mexico (Fig. 3). The original naming of these deposits was Airborne Anomalies 1–2 as designated by the original U.S. Atomic Energy Commission airborne survey. Bingler (1968) named the deposits Stinking Lake, after a nearby lake. The name of the deposits was changed from Stinking Lake to Apache Mesa at the request of some Tribal members.

The Jicarilla Apache Reservation was established in 1887 and expanded several times since. There are approximately 3,400 tribal members (http://www.bia.gov/WhoWeAre/RegionalOffices/Southwest/What/index.htm; accessed 6/1/16), most live in the town of Dulce, north of Apache Mesa (Fig. 3). Dulce is the only town on the Jicarilla Apache Reservation. Farmington is approximately 84 mi west of Dulce and Pagosa Springs, Colorado is north of Dulce.

Access

U.S. 64, NM 17 and NM 537, cross the reservation (Fig. 3). Apache Mesa is accessed by Highway J8 (paved), south out of Dulce. A dirt road, J48, leads from J8, south of Boulder Lake to Apache Mesa (Fig. 4).

Physiography

The Apache Mesa area in eastern Rio Arriba County is on the edge of the Colorado Plateau and Southern Rocky Mountain physiographic provinces. Eastern Rio Arriba County consists of moderately rugged, forested mesas separated by broad bushy valleys. The Continental Divide is west of Apache Mesa. Apache Mesa consists of rough terrain with steep slopes, narrow canyons and broad, flat mesas (Fig. 4). Elevations range from 7,000 to 8,000 ft.

Climate

The climate of Apache Mesa is semiarid, with warm summers and cold winters (Table 2). Monsoon rains in the summer and snow in the winter provide most of the precipitation (Table 2).

TABLE 2. Summary of climate data for Dulce, New Mexico at an elevation of 6,791 ft (http://www.usclimatedata.com/climate/dulce/new-mexico/united-states/usnm0096, accessed on 6/1/16).

	January	April	August	November	Year
Average high temperature °F	43	63	84	53	64.5
Average low temperature °F	8	26	48	19	27.8
Average precipitation in inches	1.42	1.26	2.68	1.46	18.4
Average snowfall in inches	14	3	0	6	58

FIGURE 3. Location of Apache Mesa deposit, Jicarilla Apache Reservation, Rio Arriba County, New Mexico.

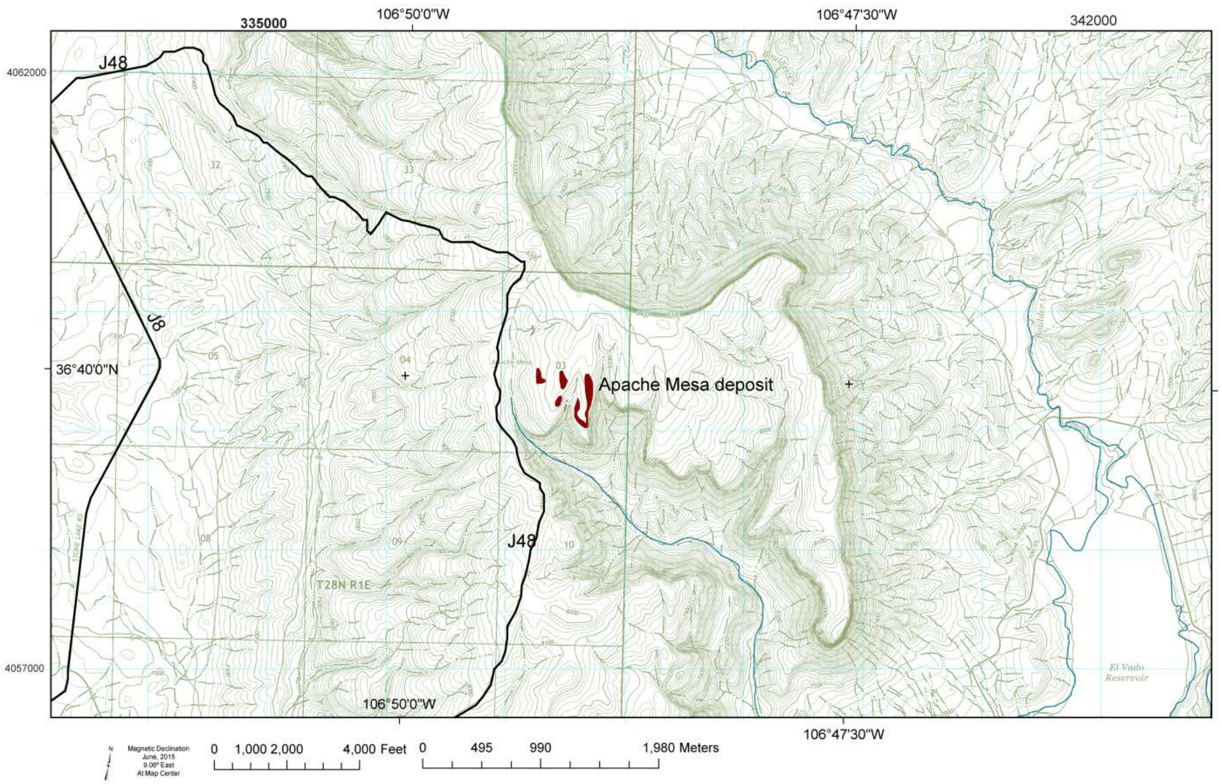


FIGURE 4. Topographic map of Apache Mesa deposit, Jicarilla Apache Reservation, Rio Arriba County, New Mexico (Apache Mesa topographic quadrangle).

Vegetation and Wildlife

Vegetation ranges from spruce-aspen cover at the highest elevations through large areas of pinon-juniper. There are no known endangered species or vegetation within the project area. Apache Mesa is forested with vegetation covering much of the rock units, except along steep cliffs.

Infrastructure

There are no known archeological sites or environmental concerns within the project area. Cell phone coverage is spotty. During more than 35 yrs of gas and oil activity within the Jicarilla Apache Reservation, more than 2,700 wells were drilled, predominantly in the southern half of the reservation (Segerstrom and Henkes, 1977).

ANALYTICAL METHODS

Mapping and Sample Collection

Apache Mesa area was mapped according to standard geologic mapping techniques at 1:6,000 scale (Plate 1; Lahee, 1961; Carpenter and Keane, 2016). Each unit was examined and described, including the dip, strike, and thickness. Surface geologic units were differentiated, described and sampled as described below. The units were differentiated mostly on the basis of color, particle size, composition, stratigraphic position, dip, thickness, depositional environment, and other properties. Color is identified using a Munsell color chart.

Two bags containing 1–2 lbs of fresh rock sample were collected at each location for chemical analysis, petrographic analyses, and archived. Most samples were composite samples collected by a rock hammer across the thickness of the sedimentary unit. Samples were sent to ALS Laboratory Group for whole rock chemical analyses by X-ray fluorescence (XRF) and Induced Plasma Spectroscopy (ICP).

One stratigraphic section was measured at station SL46, just west of the western fault (Fig. 5; Appendix 2). A chip tray was collected of each unit and is archived at the New Mexico Bureau of Geology and Mineral Resources (NMBGMR).

Other areas in the San Juan Basin were examined and sampled in order to compare with the Apache Mesa deposits. These prospects also are described in the New Mexico Mines Database (McLemore et al., 2002, 2005a, b) and are identified by a unique mine identification number (Mine Id), beginning with NMOt (for example NMOt0054). Heavy mineral, beach-placer sandstone deposits along the James River and the Concord heavy mineral sands mine in Virginia also were examined and sampled in order to compare with the Apache Mesa deposit (Appendix 2).

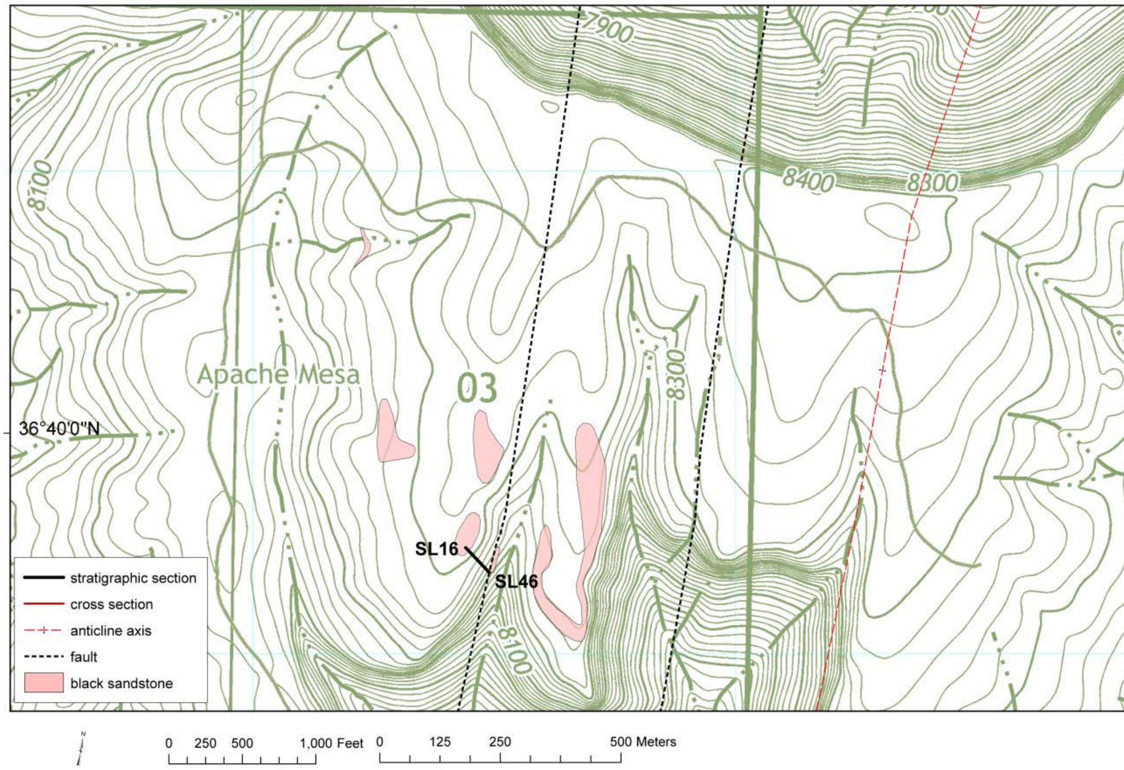


FIGURE 5. Location of stratigraphic section described in Appendix 2.

Drilling

During field investigations June 10–12, 2015, 18 proposed drill hole locations were staked in the field with wooden stakes and flagged with orange, blue, and pink flagging tape. The GPS coordinates were measured for each proposed drill site. The final drilling report is in Appendix 3. Drill hole graphic logs are in Appendix 4. Locations of final drill holes are in Figure 6.

Drilling began on August 18, 2015. A few problems were encountered during drilling and solved. The equipment was moved onto the site on August 18, 2015 and trenches for water were dug. The major delay was when the drill rig ceased to function because of fuses. After trouble-shooting for 1.5 hr, the drillers were able to get the rig going. Drilling on DH1 began on August 19, 2015. Additional difficulties were encountered (loss of circulation, improper core springs) but resolved. Drilling was completed on August 25, 2015. Table 3 summarizes the final completed drill holes. An additional hole (DH7) was located and drilled along the road south of DH5 because DH5 did not encounter much black sandstone. The road was already cleared and DH7 was on the road with little additional disturbance.

TABLE 3. 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 6 and final drilling report is in Appendix 3. Graphic logs are in Appendix 4.

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

Final Drill Hole Id	UTM easting	UTM northing	Total depth (ft)	Completion	Purpose	Summary of goals
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

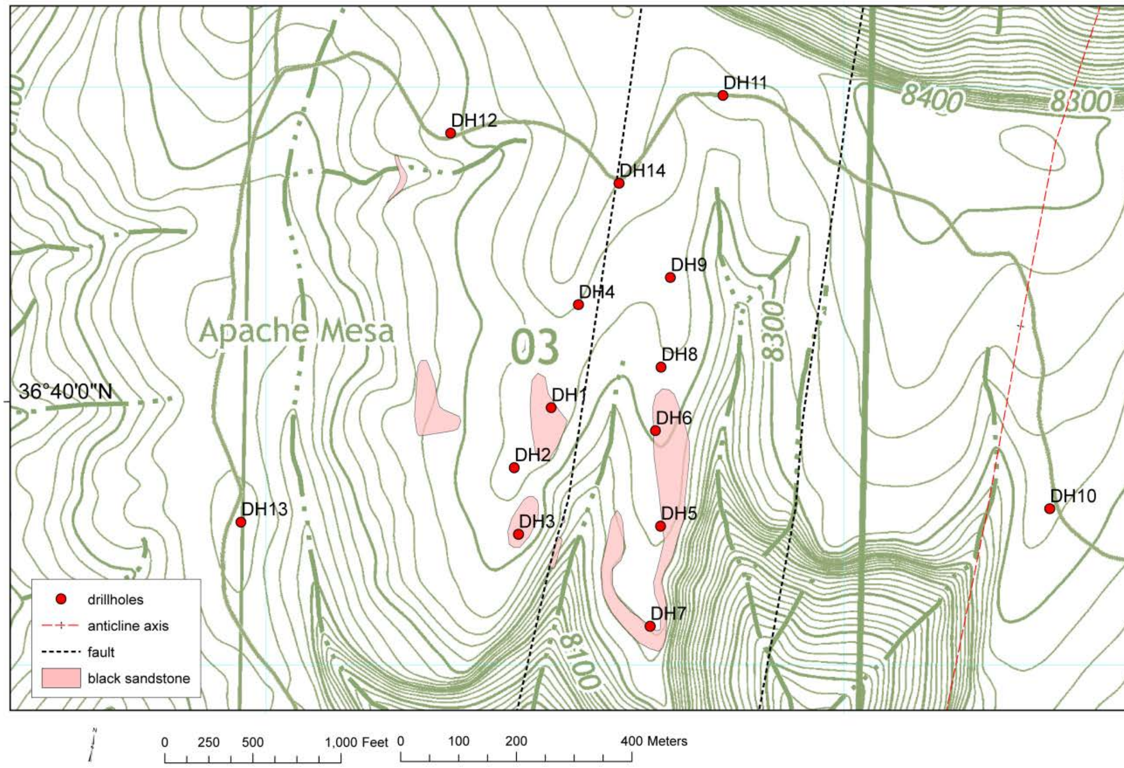


FIGURE 6. Location of drill holes on Apache Mesa, Rio Arriba County. Details are in Table 3 and Appendix 3.

Core was laid out, washed, and stored in core boxes at the drill site. The first author photographed and described in detail each core box in the field, using standard techniques (Jones and O'Brein, 2014; Carpenter and Keane, 2016). The descriptions (drill logs) were recorded on paper forms and subsequently entered into word documents (Appendix 3). The core was transported to a locked storage facility in Dulce by the senior author, and then transported to Socorro by NMBGMR personnel and stored permanently at the NMBGMR core library (http://geoinfo.nmt.edu/libraries/subsurface/home.html, accessed 6/6/16). The authors re-examined the core in Socorro and sampled selected intervals. The sampled core was split using a core splitter, cleaned after each sample was split. One quarter of the core sampled was bagged for chemical analysis and selected samples of one quarter of the core were collected for mineralogical examination and electron microprobe analyses. Samples for chemical analyses were shipped to ALS Laboratory Group in Reno, Nevada.

Petrographic Descriptions

Petrographic analyses were performed using standard petrographic (Carpenter and Keane, 2016), microscopy, and electron microprobe techniques. Thin sections were made of selected samples. Mineral concentrations and phase percentages, grain size, roundness, and sorting were estimated using standard charts (Carpenter and Keane, 2016). Data are summarized in Appendix 5. Drill core descriptions are in Appendix 3. Estimates of both primary and secondary minerals were determined, cementation and alteration described, and mineralogy and lithology described (Folk, 1974; Carpenter and Keane, 2016). Any special features were noted.

Chemical Analyses

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; http://www.alsglobal.com/Our-Services/Minerals/Geochemistry/Downloads, accessed 6/1/16). Samples were analyzed by ALS Laboratory Group for major and trace elements by a variety of analytical methods (CCP-PKG03 and Au-ICP21; http://www.alsglobal.com/Our-Services/Minerals/Geochemistry/Downloads, accessed 6/1/16), including X-Ray Fluorescence (XRF), inductively coupled plasma atomic emission spectroscopy (ICP-AES), and inductively coupled plasma mass spectrometry (ICP-MS)**.** This package combines the whole rock package ME-ICP06 plus carbon and sulfur by combustion furnace (ME-IR08) to quantify the major elements in a sample. Trace elements, including the full REE suites, are performed after three digestions with either ICP-AES or ICP-MS finish: 1) a lithium borate fusion for the resistive elements (ME-MS81), 2) a four acid digestion for the base metals (ME-4ACD81) and 3) an aqua regia digestion (ME-MS42). Gold was analyzed separately (Au-ICP21). Chemical analyses are in Appendix 6; locations are in Figure 7.

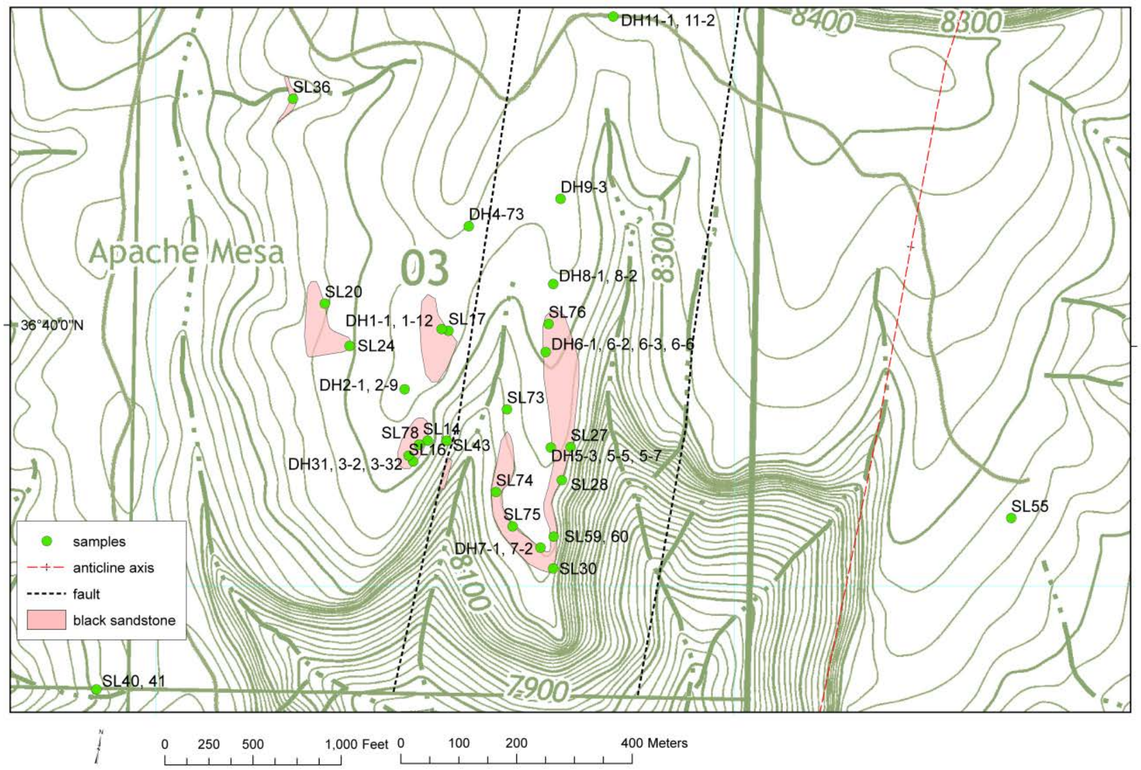


FIGURE 7. Location of surface and drill hole samples for chemical analyses. Details are in Appendix 6.

On-going control samples were submitted with each batch of samples submitted. Certified standards are commercial standards with certified values as determined by round robin analyses at numerous certified laboratories. Certified standards are expensive, so on-going control samples were analyzed instead. The on-going control samples are standards collected by NMBGMR personnel and analyzed by different methods over several years of analyses by different laboratories. Duplicate samples were also submitted. A summary of the quality control and quality assurance (QA/QC) is in Appendix 7 and McLemore and Frey (2009).

Electron Microprobe Mineralogical Analyses

Samples of beach-placer sandstones were examined using a Cameca SX100 electron microprobe with three wavelength-dispersive spectrometers at New Mexico Institute of Mining and Technology to characterize compositional, chemical and textural characteristics. Samples chosen for microprobe analysis were selected based on elevated whole-rock chemical concentrations of

TiO_2, Zr, U, Th, and REE. Samples cut to an appropriate size were placed in 1 inch round sample mounting cups, set in epoxy, and cured overnight at around 80° C. Once cured, samples were polished using coarse diamond grinding wheels and diamond power suspended in distilled water for the fine polishing. Polished sample surfaces were then cleaned using petroleum ether and carbon coated to a 200 angstrom thickness.

Three types of analyses were performed. The initial observations of the samples were made using backscattered electron imaging (BSE), which allowed observation of sample textures, and location of high mean atomic number (Z) phases that may contain TiO_2, Zr, U, Th, and REE, and other high Z elements. BSE observations were coupled with acquisition of rapid X-ray maps and/or qualitative geochemical scans, which allow qualitative assessment of the elements present in a given mineral phase. Peaks that appeared on the scans were identified using Cameca software. The elements shown by the peaks and their relative abundance of the elements, based on peak height, were used to identify the mineral phases. Qualitative scans were carried out using an accelerating voltage of 15 kV and a probe current of 20 nA. Descriptions of the microprobe analyses are in Appendix 8.

The third types of analyses, quantitative, of monazites from selected samples were determined (Appendix 9). The analytical setup for these phases included a total of 14 elements. A 20 kV accelerating voltage, a 40 nA probe current, and a focused beam were used for these analyses. Matrix corrections for monazite analyses were carried out using the ZAF method. Analytical totals for many of the REE-bearing phases were less than 100%, due to the presence of unanalyzed components in many of the mineral structure. Oxygen was determined stoichiometrically, using normal oxidation states for all elements (i.e. SO_2, TiO_2, Cr_2O_3, Fe_2O_3). A summary table of all analyses is shown on the first tabbed page of Appendix 8. The following pages show the datasets for the two analytical sessions (session 1 and session 2). Summary datasets are given for both sessions, as well as “Details” pages. The analytical details, including count times, peak and background count rates, analytical precision, and detection limits are listed in the “Details” tabbed pages. For more information on the electron microprobe laboratory see http://geoinfo.nmt.edu/labs/microprobe/home.html (accessed 6/1/16).

Specific Gravity Measurements

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. A fresh piece of sample, approximately 1 g, is broken off, dried, weighed in air and weighed when submerged in distilled water. Specific gravity is defined by weight in air /(weight in air – weight in water). Specific gravity measurements are in Table 4.

TABLE 4. Specific gravity measurements for selected samples. Sample locations and descriptions are in Appendix 5. Specific areas are described below.

Sample	Location	Weight in Air (g)	Weight in Water (g)	Specific Gravity
DH 1-1	Apache Mesa	13.50	7.50	2.40
DH 3-1	Apache Mesa	3.50	2.50	3.50
DH 3-2	Apache Mesa	2.00	1.00	2.00
DH 3-3	Apache Mesa	9.50	5.50	2.38
DH 5-3	Apache Mesa	6.00	3.50	2.40
DH 5-7	Apache Mesa	6.00	3.50	2.40
DH 7-1	Apache Mesa	4.00	2.50	2.67
SL 16	Apache Mesa	3.00	2.00	3.00
SL 28	Apache Mesa	4.00	2.50	2.60
SL 59	Apache Mesa	2.50	1.50	2.50
SL 60	Apache Mesa	1.50	1.00	3.00
SL 74	Apache Mesa	6.50	4.00	2.60
SL 78	Apache Mesa	4.50	3.00	3.00
FT 2	Standing Rock, San Juan Basin	2.50	1.50	2.50
FT 3	Standing Rock, San Juan Basin	7.00	4.00	2.33
Hovey 1	B.P. Hovey, San Juan Basin	5.00	4.00	5.00
SAN 1	Sanostee, San Juan Basin	2.00	1.00	2.00
SAN 2	Sanostee, San Juan Basin	4.00	2.50	2.60
SAN 3	Sanostee, San Juan Basin	2.50	1.50	2.50
SAN 6	Sanostee, San Juan Basin	2.50	1.50	2.50
VA 7-15	Virginia	4.50	1.00	1.29
VA 3	Virginia	8.50	3.00	1.54

Calculation of Ore Resources

Unlike most types of deposits, mineral sands are generally reported in terms of percentage of minerals, specifically percent ilmenite, rutile, zircon, and so forth (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. TREE is a proxy for the amount of monazite.

Since the Apache Mesa deposit is 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 is summarized in Table 5. The deposit was divided into polygons surrounding either a surface or drill hole sample location (Fig. 8). Note that two ore blocks, 19 and 20 are in the subsurface. The area of each polygon was determined using the GIS area calculation tools. The thickness was determined by the drill-core interval or measured at the surface. The tonnage of each polygon was determined by:

$$A \times T \times SG$$

where A=area, T=thickness, and SG = specific gravity.

The grade of each sample was determined from chemical analyses (Appendix 6). The tonnage of each element for each polygon was determined by:

$$Gp/Tp$$

where Gp=grade of each polygon and Tp=tonnage of each polygon.

The total tonnage of the deposit is the sum of the tonnage for each polygon and the total grade for each element is determined by:

$$Te/T$$

where Te=tonnage of each element of each polygon and T=total tons of the deposit.

The results are in Appendix 10.

These are simple calculations that do not account for metallurgical considerations or particle size distributions (Jones and O'Brien, 2014). Tonnage estimates are dry tonnage without any account of moisture. No cut-off grade was used. No metallurgical or marketing factors were accounted for. Open pit mining was assumed. These grade and tonnage calculations do not conform to Canadian 43–101 criteria (http://web.cim.org/standards/documents/Block484_Doc111.pdf, accessed 6/1/16) and are only preliminary estimates. Ore reserves for each polygon are in Appendix 10.

TABLE 5. 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

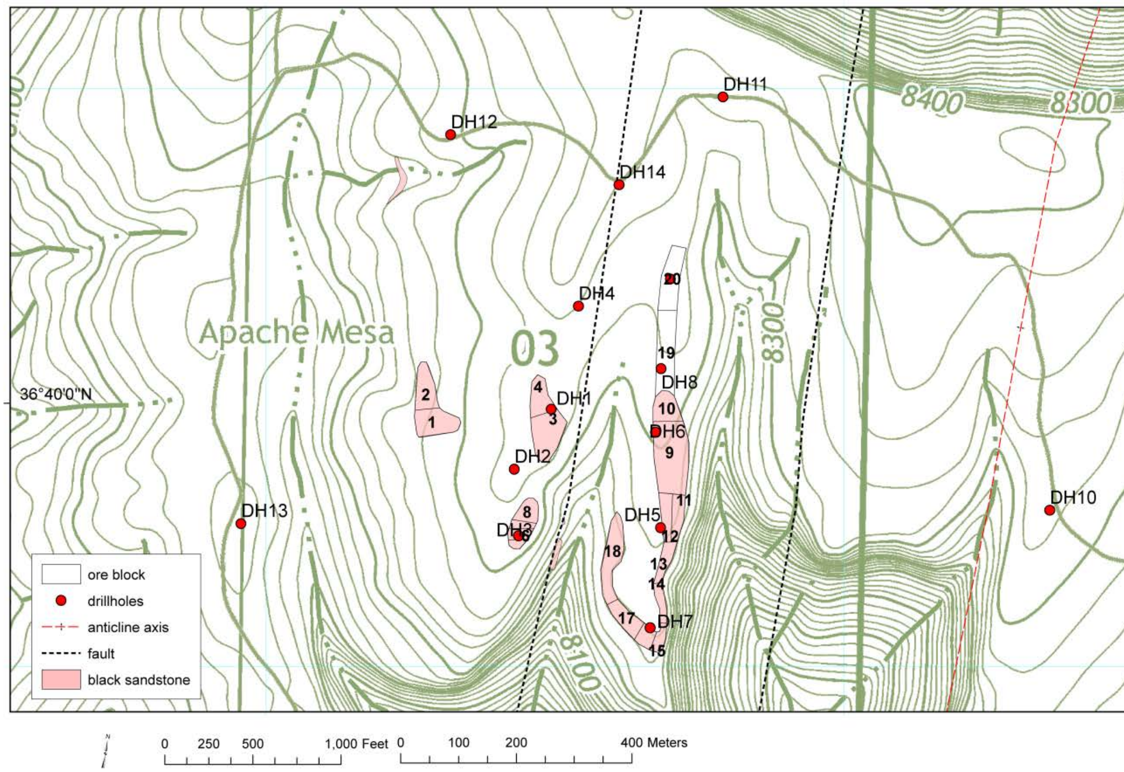


FIGURE 8. Location of polygons for calculating the ore reserves at Apache Mesa. Note that two ore blocks, 19 and 20 are in the subsurface. The two polygons without numbers cannot be mined because of steep topography.

Quality Control Procedures and Sample Security

Samples were collected, prepared, and analyzed according to standard methods for each specific laboratory analysis. Samples were collected in the field and kept under direct control of the senior author to avoid contamination. Samples are archive at the NMBGMR. Samples collected are complete, comparable, and representative of the defined population at the defined scale as documented in Appendix 7. Precision and accuracy are measured differently for each field and laboratory analysis (parameter), and are explained in the methods section of this report and Appendices 7 and 9 and McLemore and Frey (2009). Most geochemical laboratory analyses depend upon certified or on-going reference standards and duplicate analyses (Appendix 7). The sampling and analysis plans for each segment of the field and drilling program and the control of accuracy and precision as defined here, provides a large high-quality set of observations and measurements that are adequate to support the interpretations and conclusions of this report. Field and laboratory audits by the senior author were performed to ensure that procedures were followed.

REGIONAL GEOLOGICAL SETTING

During the Late Cretaceous, the present San Juan Basin was on the western edge of the Western Interior seaway (Robinson-Roberts and Kirschbaum, 1995), which extended from the Gulf of Mexico to the Arctic Ocean. Complex fluvial systems transported sediments from the volcanic and metamorphic sources in the Mogollon Highlands and Ancestral Rocky Mountains to the south and west into the basin. Cyclic transgressions and regressions of the marine seas resulted in a shift of the paleoshorelines. Most of the heavy mineral, beach-placer sandstone deposits define local depositional trends of the beaches at the time of deposition. The shoreface sandstone deposits in the San Juan Basin were formed both during transgression and regression of the western edge of the Western Interior Seaway (Robinson-Roberts and Kirschbaum, 1995; Fassett, 2000) and are similar to deposits on the Atlantic Coast in the United States (Koch, 1986; Carpenter and Carpenter, 1991), southeastern Australia (Roy, 1999), and Andhra Pradesh, India (Rao et al., 2008).

GEOLOGY OF APACHE MESA

Geologic Setting

The Point Lookout Sandstone crops out around the margins of the San Juan Basin, forms cliffs or caps mesas or resistant dip slopes and hogbacks, is of variable thickness, and is a regressive-transgressive sandstone (Hollenshead and Pritchard, 1961; Tabet and Frost, 1979; Craigg et al., 1990; Devine, 1991; Zech et al., 1994). It conformably overlies the Mancos Shale and is overlain by the Menefee Formation (Fig. 9). The Point Lookout Sandstone was deposited in upper shoreface, foreshore, washover, and eolian environments as the Cretaceous sea regressed to the east and north across the San Juan Basin (Landis at al., 1974; Fassett, 1977; Zech, 1982; Zech et al., 1994). The Point Lookout Sandstone is between 85 and 80 million yrs and accumulation rates ranged from 26–60 m/m.y. (Cather, 2004).

At Apache Mesa, the Point Lookout Sandstone is 100–150 ft thick, forms cliffs, and overlies the Mancos Shale (Fig. 10, 11; Plate 1, 2). The older, underlying Mancos Shale typically forms slopes covered by talus deposits eroded from the Point Lookout cliffs (Fig. 11). Much of Apache Mesa is forested and the outcrops vary from poor to a few well exposed areas.

Three distinct, informal units within the Point Lookout Sandstone are mapped at Apache Mesa (Fig. 10): 1) older yellow sandstone, 2) white sandstone, and 3) younger black sandstone. The older yellow sandstone unit consists of yellow, massive to laminated cross-bedded to high-angle cross-bedded, subangular to rounded, well to moderate sorted, fine- to medium-grained sandstones (Fig. 12; Appendix 2, 3). Some beds show evidence of bioturbation and burrows. This unit is interpreted to have been deposited in off-shore environments, which are unfavorable for formation of heavy mineral, beach-placer sandstone deposits.

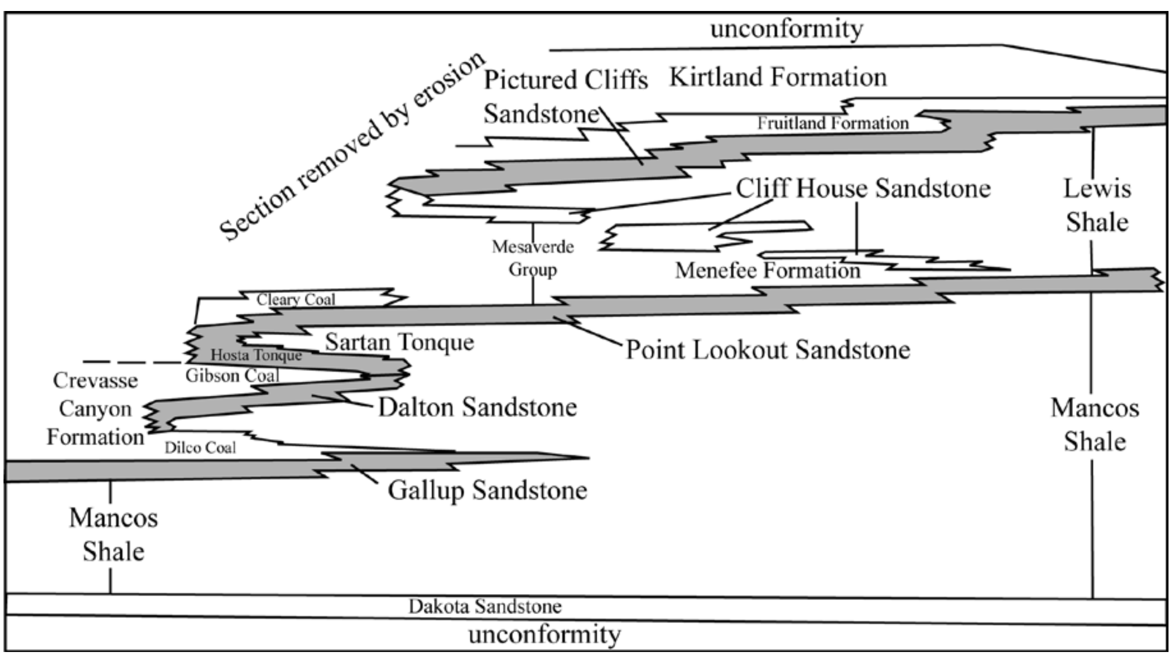


FIGURE 9. Stratigraphic framework and nomenclature of the Late Cretaceous sedimentary rocks in the San Juan Basin (simplified from Molenaar, 1989; Craigg et al., 1990). Gray-shaded sandstone units are hosts of known beach-placer sandstone deposits in the San Juan Basin.

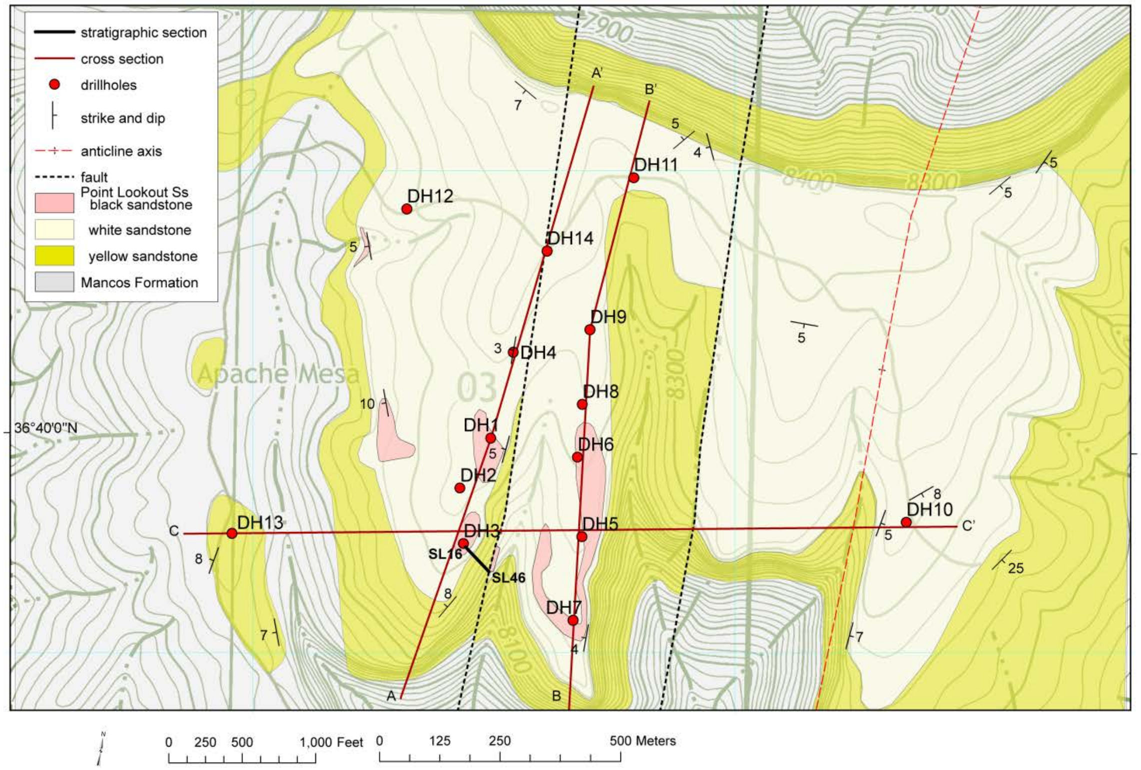


FIGURE 10. Geologic map of the Apache Mesa area, Rio Arriba County, New Mexico (see Plate 1). Cross sections are below and shown in Plate 2.

FIGURE 11. Point Lookout Sandstone forming cliffs overlying Mancos Shale (covered slopes) at Apache Mesa (looking east). Photograph by V.T. McLemore.

FIGURE 12. Trough cross beds in the yellow sandstone on Apache Mesa. Photograph by V.T. McLemore.

The middle unit consists of white, light gray to olive gray, massive to planar cross-bedded, medium- to fine-grained, moderately to well sorted sandstone (Fig. 13), locally with trough cross-stratification. This unit is interpreted to have been deposited in the beach environment (Fig. 1), which is favorable for formation of heavy mineral, beach-placer sandstone deposits.

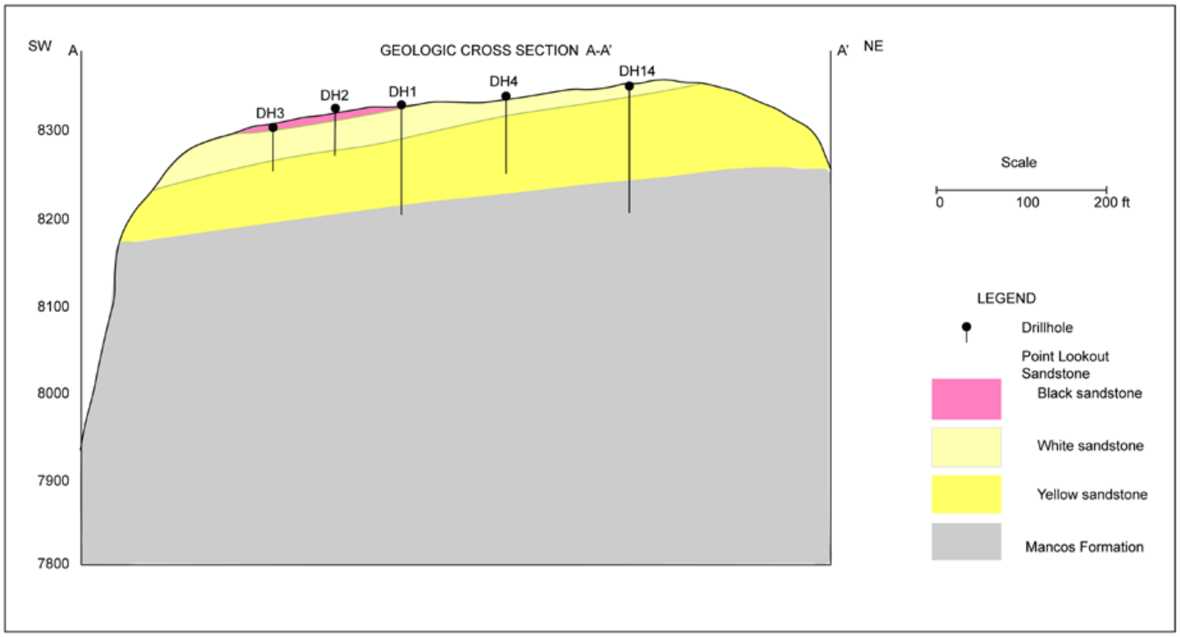
FIGURE 13. Contact between the older, underlying yellow sandstone and younger, overlying white sandstone (below clipboard). Photograph by V.T. McLemore.

The younger black sandstone consists of less than 1 ft to 9.9 ft and thickens near DH7 (Appendix 4, 9) and thins to the north and west. It is not exposed on the eastern mesa (Fig. 10, Plate 1). The Apache Mesa deposits are lenses (Fig. 10, 14) that overlie the white sandstone of the Point Lookout Sandstone (Fig. 14). The black sandstone is reddish-purple to olive-brown to grayish red to black red (Fig. 15), moderately to well cemented, medium-grained, and contains iron oxide minerals, leucoxene, zircon, tourmaline, rutile, magnetite, monazite, chromite, ilmenite, and gold. Locally, the black sandstone is planar bedded consisting of alternating layers of millimeter to centimeter thick, gray and red to dusky red sandstone (Fig. 15). The deposit does extend to the north in DH8 and DH9 (Fig. 8). There is a thin, black sandstone bed found in DH11, but it does not contain high enough TiO_2, Zr, or TREE to be included in the ore reserve calculations. The black sandstone was not found on the north edge of the cliff. This unit was deposited along the foreshore of the beach or in the back beach environments, probably during high tide and storm surges (Fig. 1).

Along the northern rim of Apache Mesa (near DH11; Fig. 10), the uppermost Point Lookout Sandstone consists of several feet of thin interbeds of brown carbonaceous shale, black coal to humates, and white to yellow siltstones to fine-grained sandstones overlying the middle white sandstone unit with large high-angle to trough cross-stratification (Fig. 16, Plate 2). In DH11, coal overlies a thin black sandstone bed (Appendix 4). 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 report as part of the white sandstone unit of the Point Lookout Sandstone at Apache Mesa. These units were deposited in nonmarine coastal bay, swamp, lagoon, and fluvial environments, which are unfavorable for formation of heavy mineral, beach-placer sandstone deposits.

FIGURE 14. Beach-placer sandstone deposit overlying the white sandstone in the Point Lookout Sandstone at Apache Mesa. Photograph by V.T. McLemore.

FIGURE 15. Close-up of beach-placer sandstone at Apache Mesa. Photograph by V.T. McLemore.



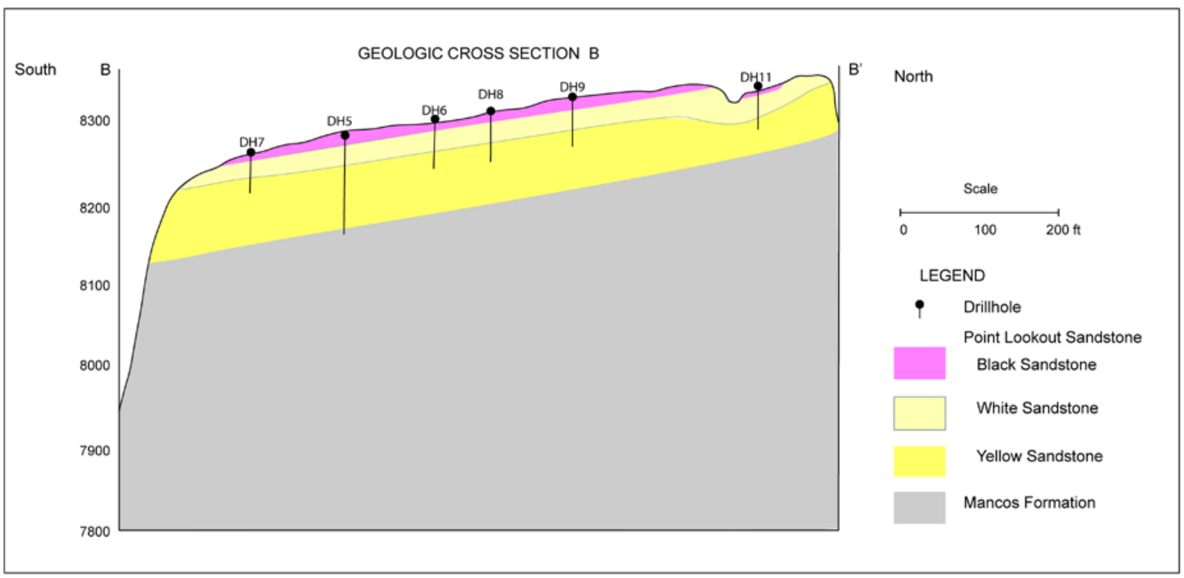


FIGURE 16. North-south cross sections (A–A', B–B') across Apache Mesa (see Plate 2). Locations of cross sections are in Figure 10 and Plate 1.

The older Mancos Shale is approximately 2,000 ft thick and is generally poorly exposed. At Apache Mesa the Mancos Shale is exposed along the western ridge and beneath Apache Mesa (Fig. 9). The Mancos Shale was encountered in DH1 (110 ft depth), DH5 (108 ft depth), DH10 (111.9 ft depth), DH13 (entire hole) and DH14 (132 ft.). The top of the 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. Most of the area surrounding the J8 and J48 roads (Fig. 4) are in Mancos Shale.

Structure

Apache Mesa is formed in part by a north-trending anticline (Fig. 10, 17, Plates 1 and 2), where the sedimentary rocks dip gently to the west or east. The rocks dip gently to the west, west of the anticline. Apache Mesa also is cut by two steeply-dipping, northeast-trending faults (Fig. 18), but the displacements along these faults are minor (Fig. 17, Plate 2). The age of the folding and faulting is likely Eocene to late Miocene (Segerstrom and Henkes, 1977).

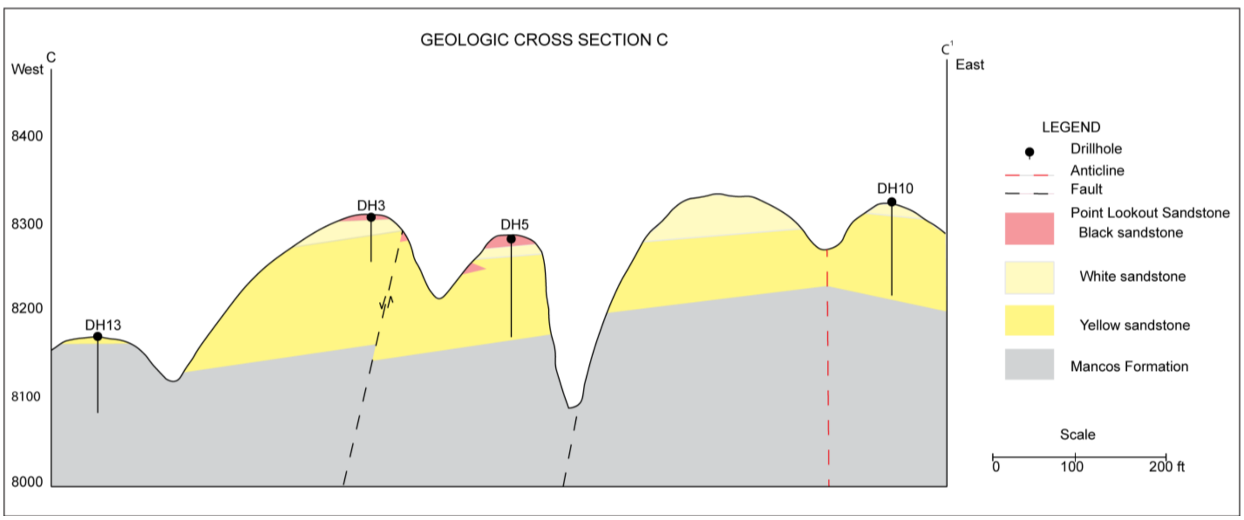


FIGURE 17. East–west cross section across Apache Mesa (C–C'; see Plate 2). Locations of cross sections are in Figure 10 and Plate 1.

FIGURE 18. Western fault trending northeast (left of Dan Koning). Photograph by V.T. McLemore.

Mineralogy and Chemistry of the Apache Mesa Beach-placer Sandstone Deposit

The majority of the samples are detrital sandstones composed mostly of quartz, some lithic fragments, feldspar, and heavy minerals. Alteration and weathering of grains appears in these samples, although the intensity varies. Cementation is composed mostly of iron oxide and some silica. Petrographic and electron microprobe results confirm the presence of iron oxides, ilmenite, rutile, zircon, monazite, xenotime, garnet and illite in these beach-placer sandstone deposits (Fig. 19; Appendix 5, 8). The grains are oblong and 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. A few grains of chromite and one grain of gold with a silver-rich rim also are found in the Apache Mesa deposit. Gold particles with silver-rich rims are common in placer gold deposits (Luterbach and McLemore, 2016). Much of the ilmenite is either altered partially to hematite or is in solid solution series with hematite, typical of many beach-placer sandstone deposits (Van Gosen et al., 2014).

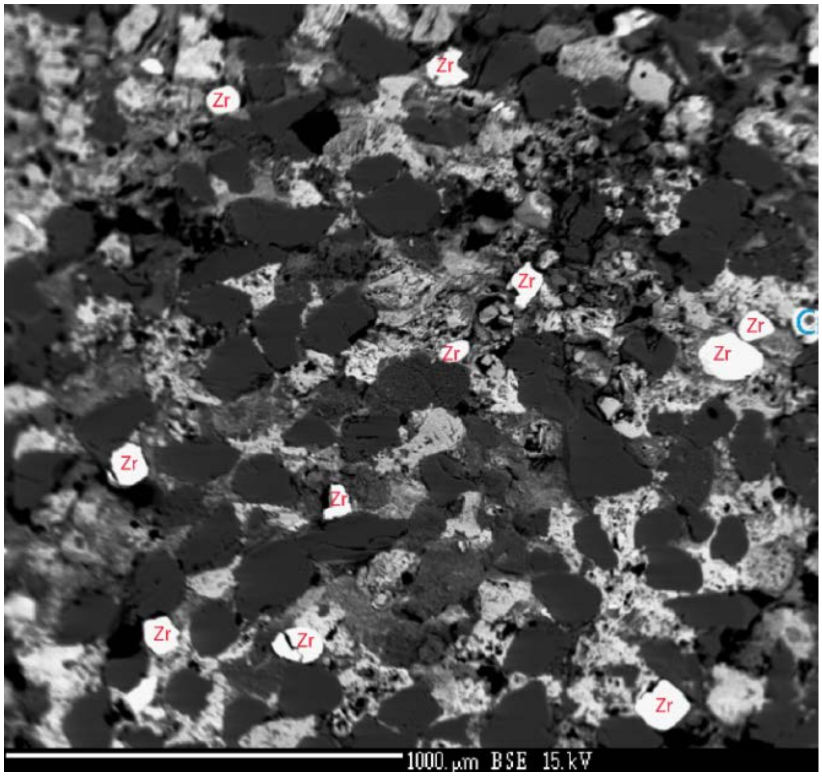


FIGURE 19. Electron microprobe picture of sample SL 16 (Apache Mesa). Zircon grains are labeled in red. Chromite is labeled in blue. Mottled, lighter colored cement is iron oxide (hematite). Dark grains are mainly quartz. Photograph by A. Robison.

Hydrology

The Apache Mesa beach-placer sandstone deposit is above the water table. All drill holes were dry, so the water table is deeper than 150 ft.

Environmental concerns

There are no environmental concerns at Apache Mesa. Impacts due to drilling were minor. Photographs of the drill sites before, during and after drilling are in Appendix 3.

DESCRIPTIONS OF OTHER BEACH-PLACER SANDSTONE DEPOSITS

San Juan Basin, New Mexico

Sanostee deposit, San Juan County

The largest exposed beach-placer sandstone deposit in New Mexico is the Sanostee deposit (NMSJ0088), which lies along the top of a mesa northwest of Sanostee, New Mexico on the Navajo Indian Reservation (Fig. 1, 20; Bingler, 1963; Force, 2000; McLemore, 2010). The

Sanostee deposit is in an olive-green-gray to dark brown to black, medium- to fine-grained, well to moderately sorted, heavy mineral, beach-placer sandstone with rounded to subrounded grains and little to no cross bedding that overlies a white to buff, moderately-well cross bedded, medium-grained sandstone, with local rust staining within the Gallup Sandstone (Fig. 21). The deposit trends N30°W, dips 5–10°W, is approximately 7,800 ft long (Fig. 20), 500–600 ft wide, 3–12 ft thick, and is overlain by black to gray shale and gray siltstone and sandstone. The deposit occurs in two separate vertical zones forming a resistant, cliff-forming ledge along the mesa (Fig. 20; Force, 2000; V.T. McLemore, field mapping, 2010, 2015). There are local mudcracks in the sandstone beds beneath the heavy mineral sandstone. The deposit contains ilmenite, magnetite, hematite-ilmenite, zircon, tourmaline, garnet, hematite, staurolite, apatite, barite, sphene, monazite, and rutile (Fig. 22; Appendix 5; Bingler, 1963; Force, 2000; Force et al., 2001).

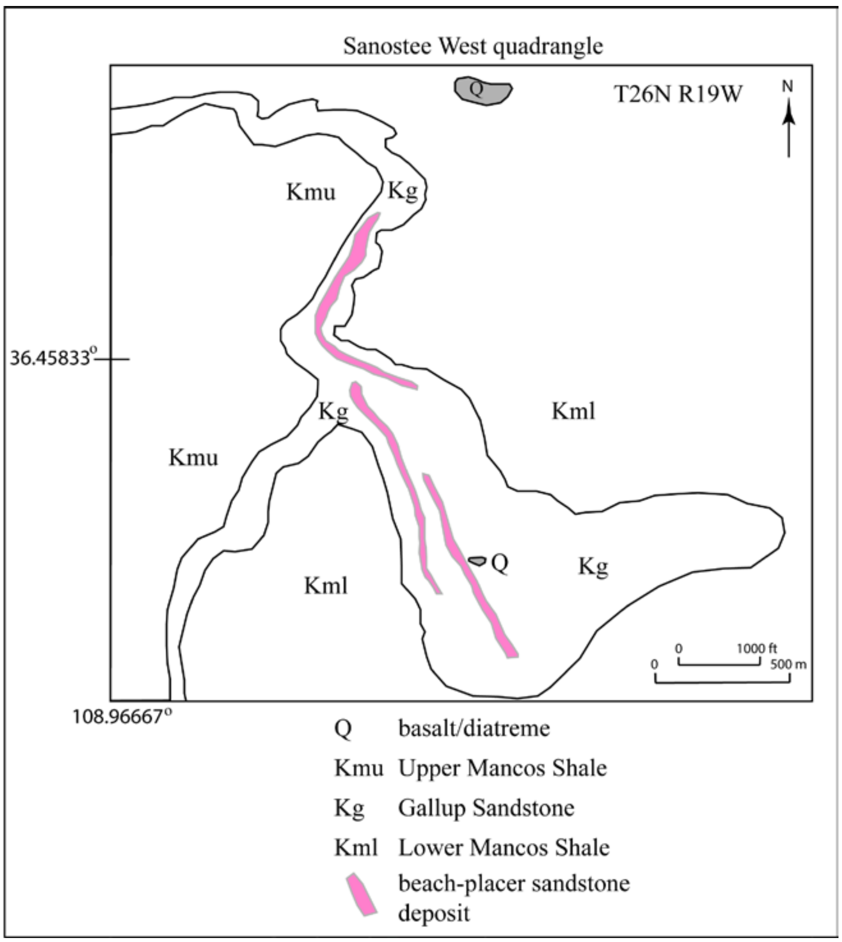


FIGURE 20. Geologic map of the Sanostee beach-placer sandstone deposits, in section 31, T26N, R19W, McKinley County, New Mexico. Mapping of the deposit was by V.T. McLemore

in 2009, modified from Beaumont (1954), Dow and Batty (1961), Bingler (1963), and Force (2000).

FIGURE 21. Beach-placer sandstone at Sanostee, McKinley County, New Mexico. Photograph by V.T. McLemore.

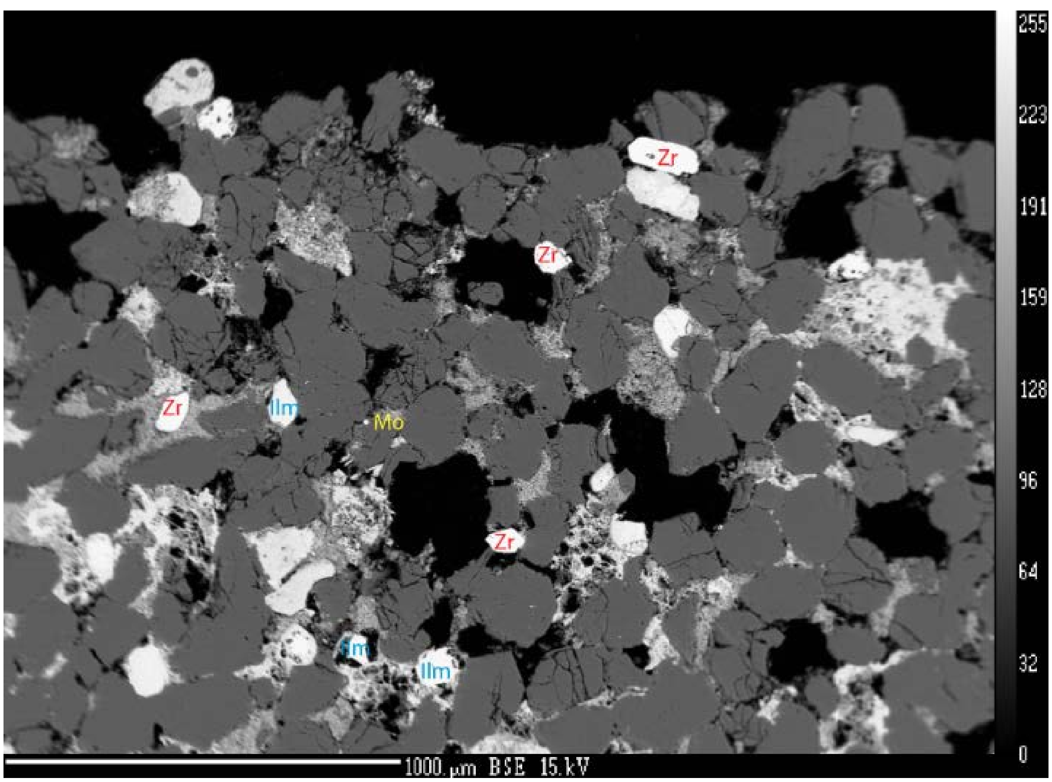


FIGURE 22. Electron microprobe photo showing distribution of zircon, ilmenite and monazite grains in sample SAN 6 (Sanostee). Zircon grains are labeled in red, ilmenite in blue, and

monazite in yellow. Mottled, lighter colored cement is iron oxide (hematite). Dark gray grains are mainly quartz. Black areas are pore spaces. Photograph by A. Robison.

Standing Rock (Flat Top Hill) deposit, McKinley County

The Standing Rock deposit (also known as Flat Top Hill, NMMK0261), in section 35, T18N, R14W, is on the Navajo Indian Reservation (Fig. 1, 23, Table 1), is a dark orange-brown to yellow to red-brown, well-cemented, medium- to fine-grained, well to moderately sorted, sandstone lens with no cross bedding in the Point Lookout Sandstone (Fig. 24). It caps the mesa top of Flat Top Hill (Fig. 23; Chenoweth, 1957; Kirk and Sullivan, 1987) and overlies a tan to buff, cross bedded, medium-grained sandstone. The deposit is as much as 5 ft thick, 100 ft wide, and consists of at least two lenses striking N50°W for approximately 5,000 ft. Calcite veining cuts the sandstone deposit locally. The deposit contains monazite, ilmenite, anatase, leucoxene, rutile, zircon, and magnetite (Appendix 5). Mud cracks are found along the mesa, indicating subaerial exposure.

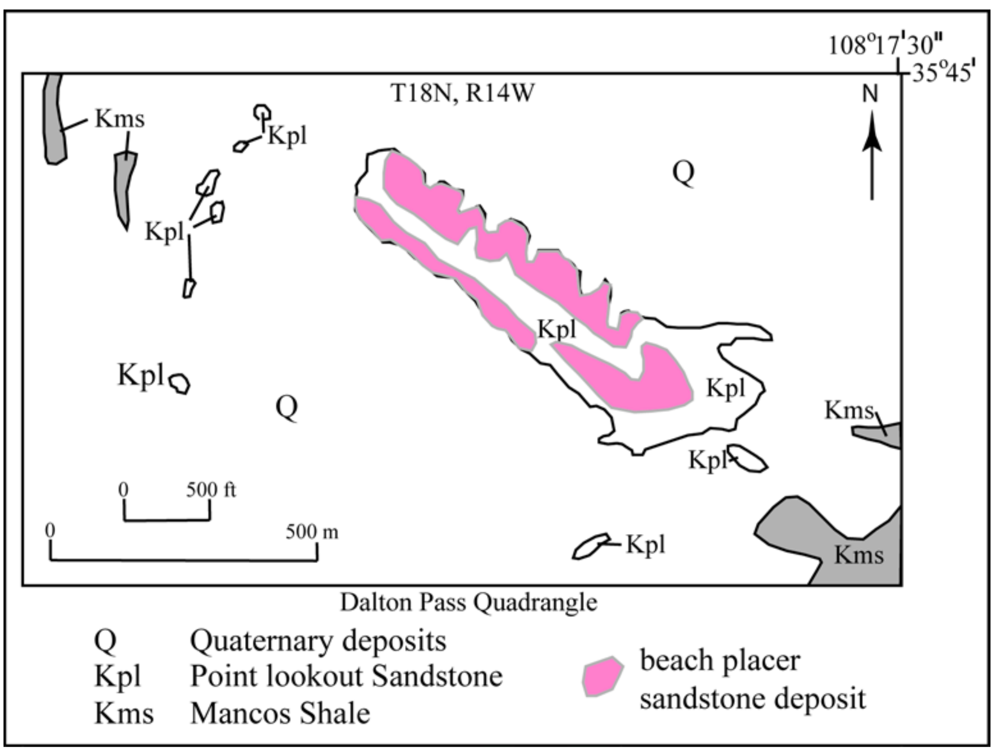


FIGURE 23. Geologic map of the Standing Rock beach-placer sandstone deposit in section 35, T18N, R14W, McKinley County, New Mexico. Mapping of the deposit was by V.T. McLemore in 2009, sedimentary geology modified from Kirk and Sullivan (1987).

FIGURE 24. Beach-placer sandstone at Standing Rock, McKinley County, New Mexico. Photograph by V.T. McLemore.

B.P. Hovey Ranch, Sandoval County

The P.B. Hovey Ranch deposit (also known as the Torreon Wash deposit, NMSA0028) is in section 34, T17W, R4W (Fig. 1, 25, Table 1). The deposit is in brown- to olive-gray, medium grained, well to moderately sorted sandstone and is approximately 300 ft long and 2–5 ft thick (Fig. 26). There are two zones of beach-placer deposits at the B.P. Hovey Ranch locality (McLemore, 1983). Drilling suggests that this deposit continues to the northwest (Chenoweth, 1957).

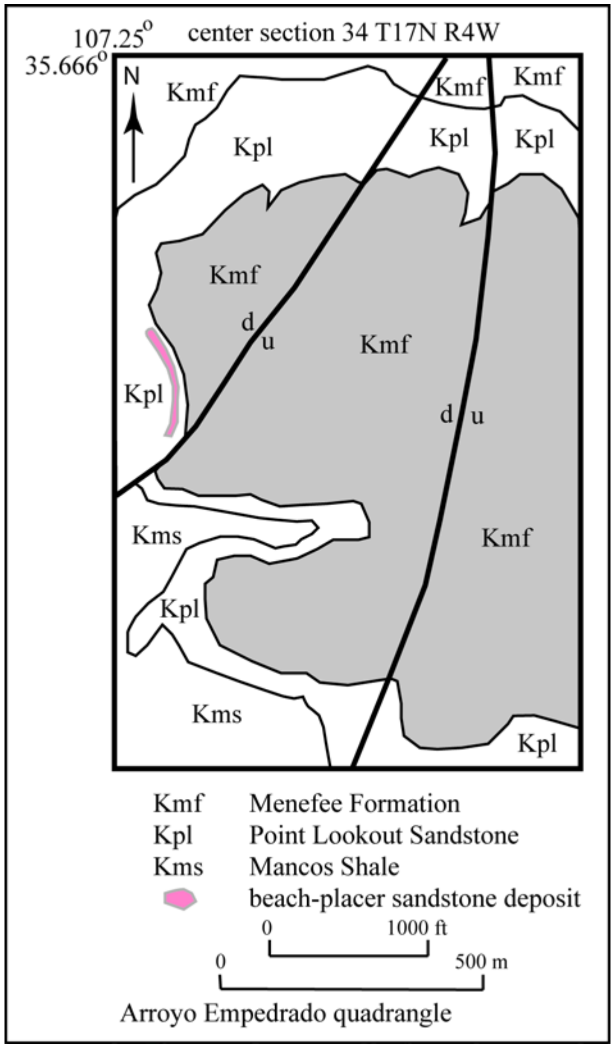


FIGURE 25. Geologic map of the B.P. Hovey beach-placer sandstone deposit, Sandoval County, New Mexico. Mapping of the deposit was by V.T. McLemore in 1981 and 2015. Sedimentary geology is modified from Tabet and Frost (1979).

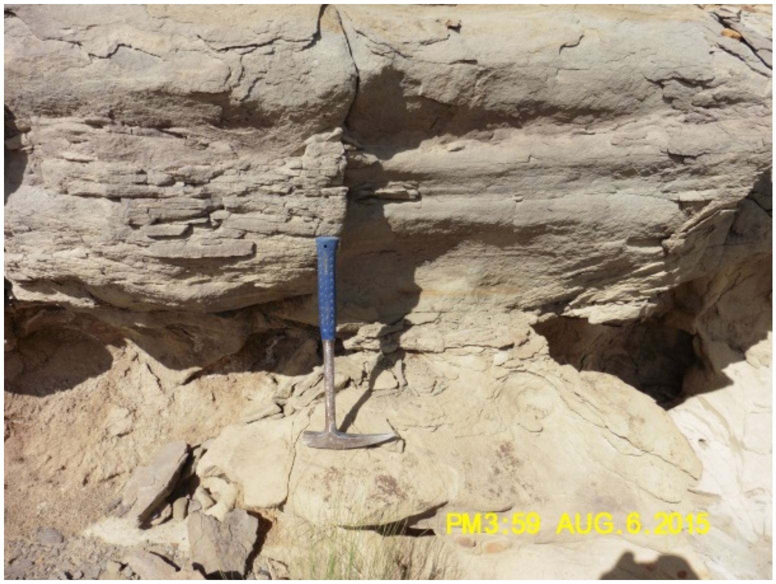


FIGURE 26. Beach-placer sandstone at B.P. Hovey, Sandoval County, New Mexico. Photograph by V.T. McLemore.

Descriptions of Pliocene beach-placer sandstone deposits, Virginia

The North American titanium province extends along the Atlantic coast from Labrador to Florida where heavy minerals are mined mostly for titanium and zircon since 1919 (Carpenter and Carpenter, 1991; Pirkle et al., 2009; Van Gosen et al., 2014). These deposits contain 40–60% ilmenite, 2-5% rutile, and 8-15% zircon formed in beach bar, dune and stream sediments along the coast. Resources were estimated as 25 million short tons containing 60% ilmenite, 2.5% rutile, 12.5% zircon, 8.5% staurolite, 0.7% tourmaline, 3% kyanite, and 1.3% sillimanite in 19 deposits found along the upper coastal plain of Virginia and North Carolina (not 43–101 reserves; Carpenter and Carpenter, 1991). These beach or dune deposits were formed during the Pliocene transgressive-regressive event 3–3.5 Ma.

Along the James River in Virginia, heavy mineral, beach-placer sandstone deposits are forming today (Berquist, 2010, 2012). These deposits are small and localized (Fig. 27) and are black, thin (less than 1 ft thick), unconsolidated and consist of ilmenite, zircon, monazite, and quartz (Appendix 5; Berquist, 2010, 2012).

In southeastern Virginia, Iluka Resources recently mined heavy mineral, beach-placer sands of Pliocene and possible Miocene age from several mines. Iluka Resources Inc. (formerly RGO USA Inc.) began mining of the Old Hickory beach-placer sandstone deposit in 1997 for titanium (ilmenite, leucoxene, rutile) and zirconium (zircon). Figures 28 and 29 are typical heavy mineral, beach-placer sandstones found at the Concord mine in Virginia. These deposits formed in beach sands and dunes formed during a world-wide Pliocene transgressive-regressive event 3–3.5 Ma.

FIGURE 27. Small beach placer sandstone deposit along the James River, Virginia. This deposit is less than 1 ft thick and several 10s of ft long. It formed in a small cove along the edge of the river. Photograph by V.T. McLemore.

FIGURE 28. Orange to light brown, unconsolidated, heavy mineral, beach-placer sands mined at the Concord mine, Virginia. Photograph by V.T. McLemore.

FIGURE 29. Lenses of high-grade, black sand lenses within the lower grade sands at the Concord mine, Virginia. Photograph by V.T. McLemore.

COMPARISON OF MINERALOGY AND CHEMISTRY OF BEACH-PLACER SANDSTONE DEPOSITS

Chemical analyses of selected beach-placer sandstone deposits are in Appendix 6. Local high concentrations of Ti, Fe, Cr, Nb, Th, U, Zr, Sc, and REE are found in in beach-placer sandstone deposits. The REE plots exhibit light-REE chondrite-normalized enriched patterns, typically with negative Eu anomalies (Fig. 30). TiO_2 and Zr show a strong correlation (Fig. 31) and U and Th show a strong correlation (Fig. 32), indicating these elements are found in similar minerals concentrated in the beach-placer sandstones.

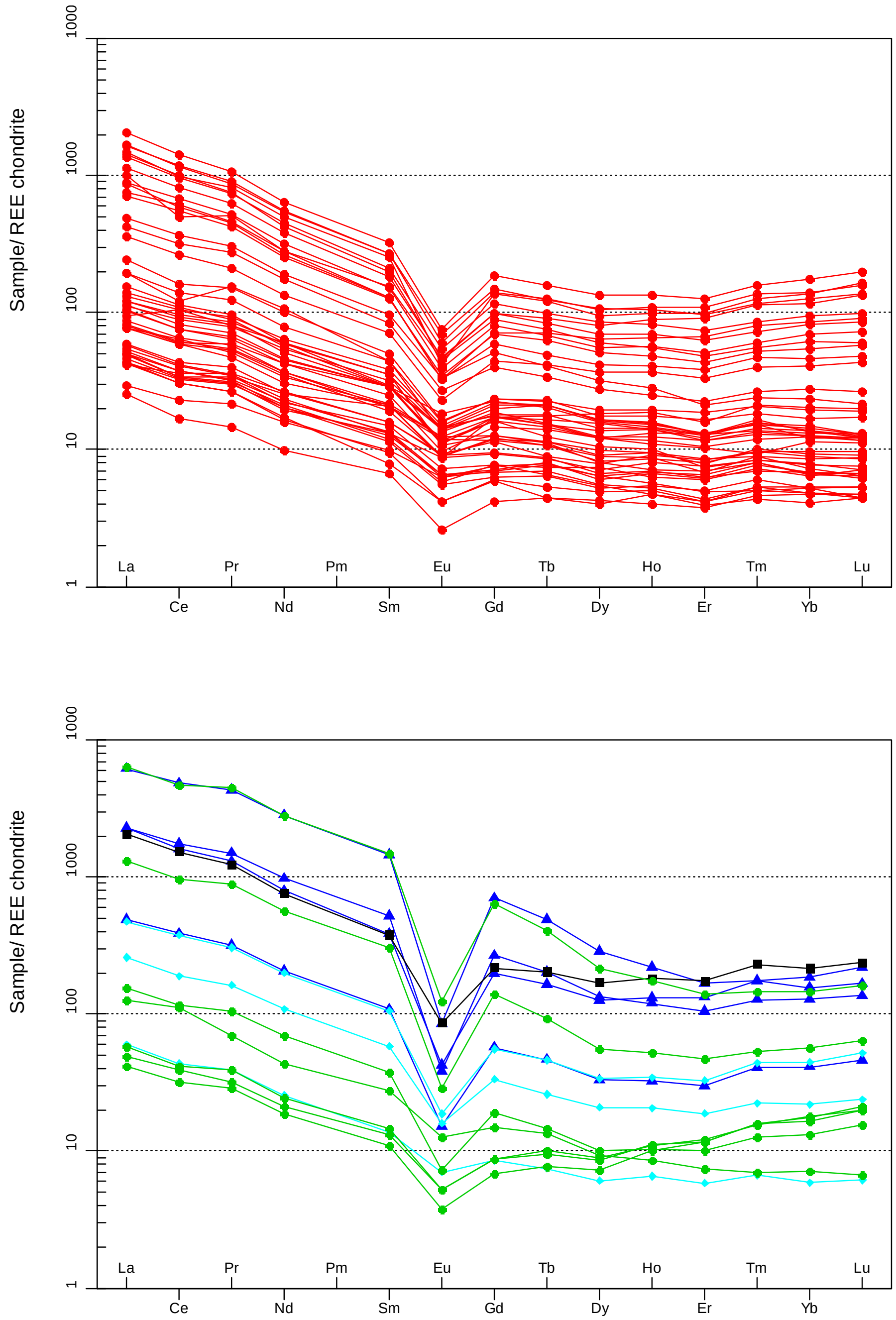


FIGURE 30. Chondrite-normalized REE plot of selected heavy mineral, beach-placer deposits, Apache Mesa (red), Standing Rock (light blue), Sanostee (dark blue), B.P. Hovey (black), San Juan Basin, New Mexico and Virginia (green). Chemical analyses are in Appendix 6. Chondrite values are from Nakamura (1974).

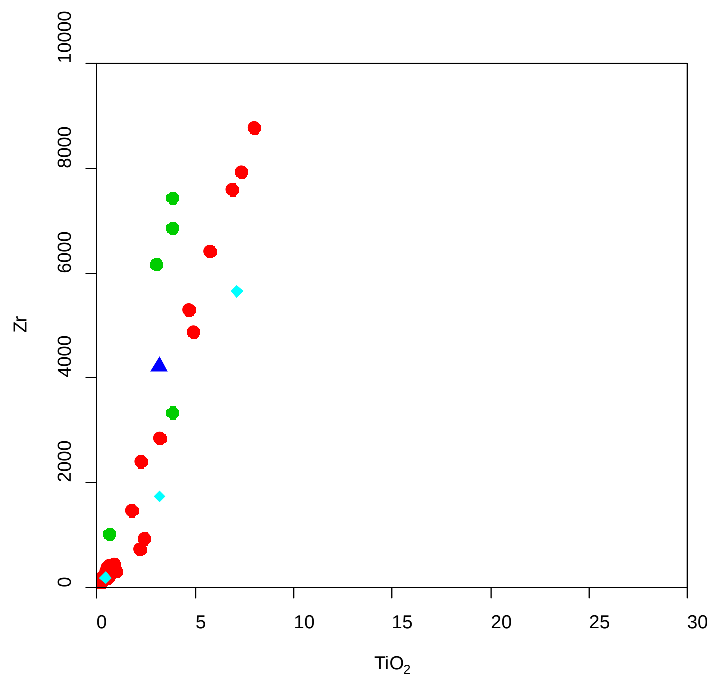


FIGURE 31. Zr-TiO_2 plot of selected heavy mineral, beach-placer deposits, Apache Mesa (red), Standing Rock (light blue), Sanostee (dark blue), and B.P. Hovey (black), San Juan Basin, New Mexico and Virginia (green). Chemical analyses are in Appendix 6.

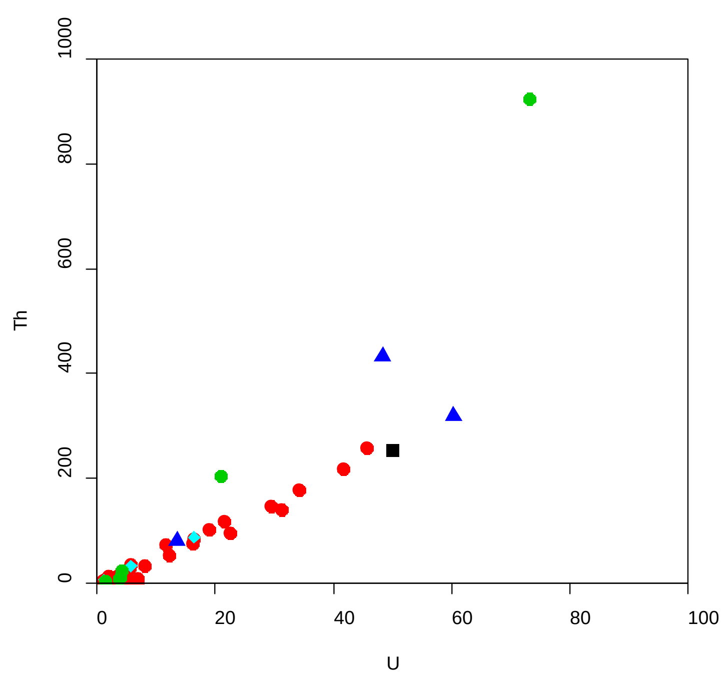


FIGURE 32. U-Th plot of selected heavy mineral, beach-placer deposits, Apache Mesa (red), Standing Rock (light blue), Sanostee (dark blue), and B.P. Hovey (black), San Juan Basin, New Mexico and Virginia (green). Chemical analyses are in Appendix 6.

Chemical analyses of monazite were determined by electron microprobe (Fig. 33; Appendix 9). These analyses are similar to chemical analyses of monazite from other mineral sand localities (Dawood and El-Naby, 2007; Van Gosen et al., 2014). Much of the uranium and thorium found in the heavy mineral, beach-placer sandstone deposits is mostly from monazite (Fig. 33), although other trace minerals are found in these deposits that also contain uranium and thorium.

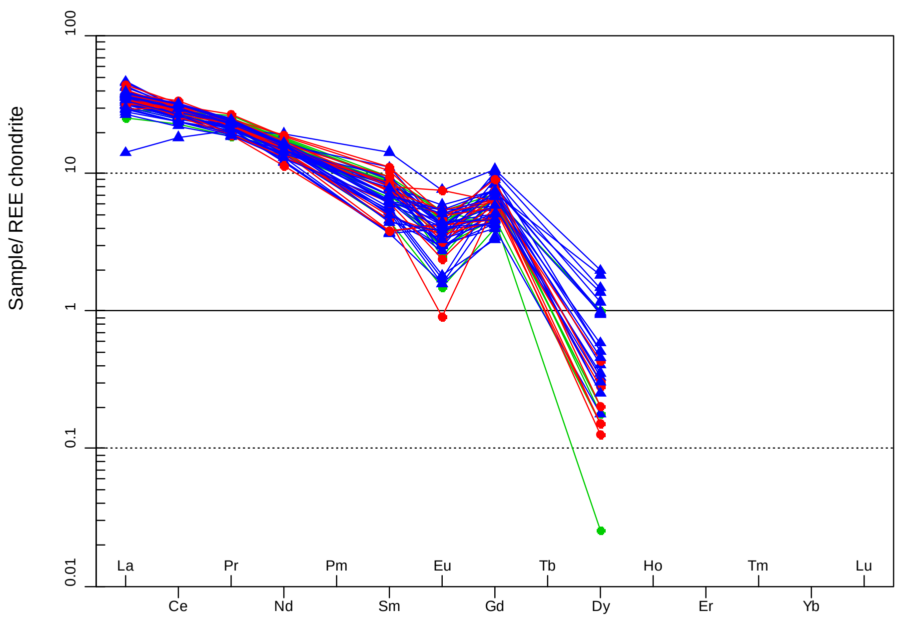


FIGURE 33. Chondrite-normalized REE plot of selected monazites from heavy mineral, beach-placer deposits, Apache Mesa (red), Sanostee (dark blue), San Juan Basin, New Mexico and Virginia (green). Chemical analyses are in Appendix 9. Chondrite values are from Nakamura (1974).

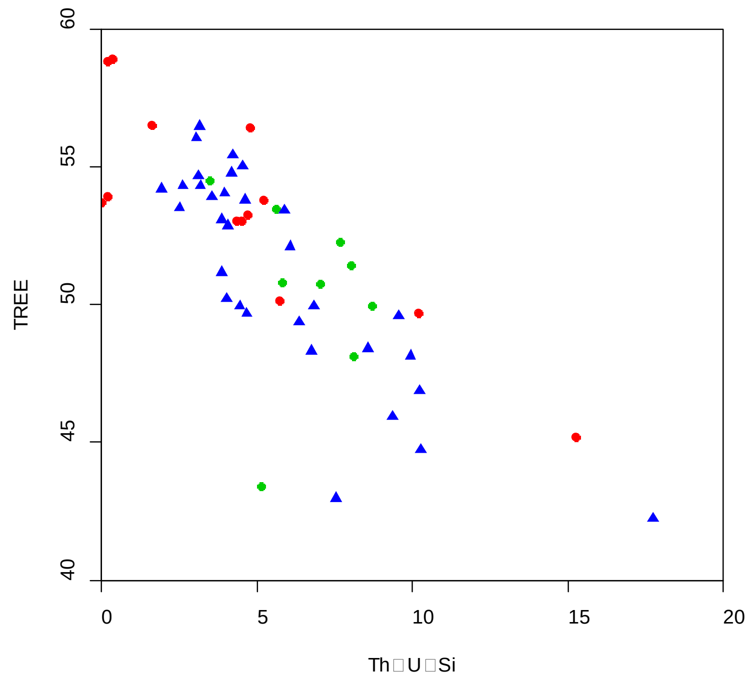


FIGURE 34. Th+U+Si verses TREE (total REE) of selected monazites from heavy mineral, beach-placer deposits, Apache Mesa (red), Sanostee (dark blue), San Juan Basin, New Mexico and Virginia (green). Chemical analyses are in Appendix 9.

ORIGIN OF BEACH-PLACER SANDSTONE DEPOSITS

The Cretaceous heavy mineral, beach-placer sandstone deposits discussed herein have many physical and chemical characteristics that are similar to modern heavy mineral, beach-placers, including host rock, 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 with dozers without any blasting. The heavy mineral, 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 deposits, which preserve them unless later erosion exposes them. In examination of titanomagnetite placer deposits along the coast of New Zealand, sorting by size rather than weight appeared to be more important in concentrating the heavy minerals (Bryan et al., 2007). The heavy minerals tend to concentrate in the upper 100 ft of the beach, decreasing in concentration 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. The Srikurmam ilmenite placer deposit in Andhra Pradesh area in India is confined between two major rivers (Rao et al., 2008) and local drainages could have controlled the formation of beach-placer deposits in New Mexico. 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 6; details are in Appendix 9. These estimates are much lower than ore reserves reported for other deposits along the Atlantic Coast, Australia, and Africa (Table 7). 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.

TABLE 6. Ore reserves for the Apache Mesa heavy mineral, beach-placer sandstone deposit, New Mexico. New Mexico data are in Appendix 9.

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

TABLE 7. Ore reserves for other heavy mineral beach-placer sandstone deposits in the world. Iluka ore reserves are from http://www.iluka.com/docs/default-source/3.2-ore-reserves-mineral-resources/annual-statement-of-reserves-and-resources2014.pdf?sfvrsn=4 (accessed 6/7/2016).

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

CONCLUSIONS

The Apache Mesa heavy mineral, beach-placer sandstone deposits are similar in appearance, texture (Appendix 5), mineralogy (Appendix 5), chemical composition (Appendix 6, 8), specific gravity (Table 4), and origin to beach-placer sandstone deposits elsewhere in the San Juan Basin and in Virginia, although the Virginia deposits are unconsolidated and have a lower specific gravity (Table 4). The Cretaceous beach-placer sandstone deposits are more cemented than the younger heavy mineral, beach-placer sandstone deposits found in Virginia, Australia, and India. 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 TREE (2,692 ppm); 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 TREE. 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.

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APPENDIX 1. GLOSSARY OF TERMS

Alteration–any change in the mineralogical composition of a rock brought about by physical or chemical means; can occur by weathering

Cross beds–layers of sediment inclined at an angle

Fault–a discreet surface separating two rock masses across which one mass has slid past the other

Formation–a body of rock identified by lithic characteristics and stratigraphic position

Fracture–general term for any surface within a material across which there is no cohesion, e.g. a crack

Geographic information system (GIS)–A computer program or system that allows storage, retrieval, and analysis of spatially related information in both graphical and database formats

Grain size and shape (Fig. A1)

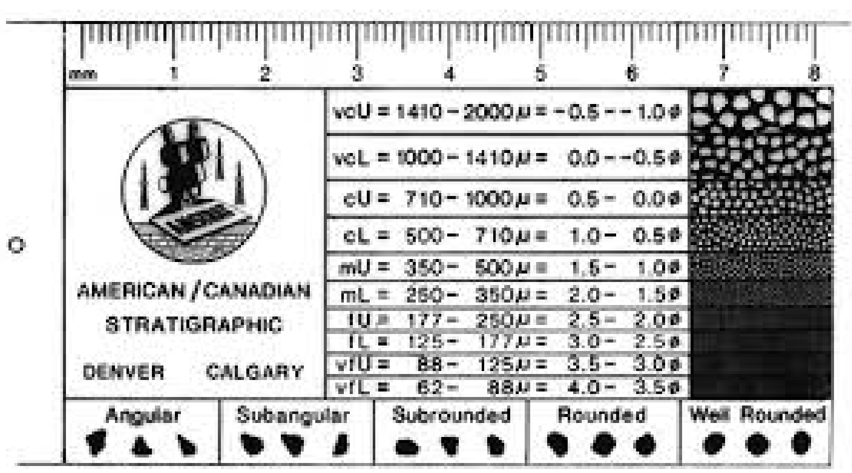

FIGURE A1. Grain size and shape of sedimentary rocks.

Heavy mineral sands–detrital minerals such as rutile, ilmenite, leucoxene, zircon, and monazite typically occurring as a sand-sized fraction, with a high specific gravity relative to that of the host sand

Lamination–thinnest layers of sediment in a unit of sedimentary rock

Lithology–the description of rocks on the basis of such characteristics as color, mineralogical composition (what minerals the rock is composed of), and grain size

Mineral deposit–any occurrence of a valuable commodity or mineral that is of sufficient size and grade (concentration) for potential economic development under past, present, or future favorable conditions.

Porosity–measure of void spaces in a material

Ore deposit-a well–defined mineral deposit that has been tested and found to be of sufficient size, grade, and accessibility to be extracted and processed at a profit over a specific time

Placer deposits–mineral deposit formed by mechanical concentration of heavy mineral particles, such as gold from weathered debris

Precision–the degree of agreement among repeated measurements of the same characteristic and monitored by multiple analyses of many sample duplicates and internal standards. It may be determined by calculating the standard deviation, or relative percent difference, among samples taken from the same place at the same time.

Quality assurance/quality control (QA/QC)–a system of procedures, checks, audits, and corrective actions to ensure that all research design and performance, environmental monitoring and sampling, and other technical and reporting activities are of the highest achievable quality

Representative sample–a portion of material that is as nearly identical in content and consistency as possible to that in the larger body of material being sampled

Sorting–refers to how similar grain sizes in a rock are (Fig. A2)

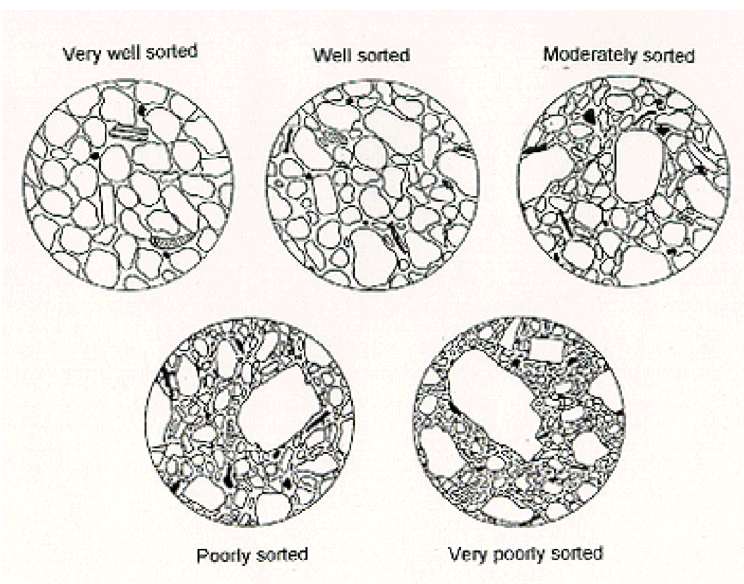

FIGURE A2. Sorting of sedimentary rocks

Texture (massive)–refers to sedimentary rock that is free from laminations and forms a single, large bed

Texture (planar)–refers to sedimentary rock that has parallel laminations within its beds

Topographic map–a map showing 2-dimensional representation of 3-dimensional changes in relief by means of contour lines

Trace minerals–minerals containing trace elements, which are elements that make up less than 1% of a mineral

Weathering–process whereby earthy or rocky materials are changed in color, texture, composition, or form (with little or no transportation) by exposure to the atmosphere