Distribution, origin, and mineral resource potential of Late Cretaceous heavy mineral, beach-placer sandstone deposits

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DISTRIBUTION, ORIGIN, AND MINERAL RESOURCE POTENTIAL OF LATE CRETACEOUS HEAVY MINERAL, BEACH-PLACER SANDSTONE DEPOSITS, SAN JUAN BASIN, NEW MEXICO

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Abstract—Beach-placer sandstone deposits are concentrations of heavy minerals that formed by mechanical concentrations (i.e. settling) of heavy minerals on beaches or in longshore bars in a marginal-marine environment. Numerous deposits are found in the San Juan Basin, New Mexico that contain high concentrations of Ti, Zr, rare earth elements (REE), Sc, Y, U, Th, Nb, Ta, Fe, and other elements. Potential sources of these deposits include Proterozoic granitic and metamorphic rocks, such as those found in the Zuni Mountains, the Jurassic arc volcanism and magmatism forming the Mogollon Highlands to the south and west, and recycling of older sediments. Many of these elements, especially Ti and REE (including Y and Sc), 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, wind turbines, etc. It is unlikely that any of the heavy mineral, beach-placer sandstone deposits in the San Juan Basin will be mined in the near future because of small tonnage, low grades, high degree of cementation through lithification, high iron content, and distance to processing plants and markets. However, as the demand for some of these elements increases because of increased demand and short supplies, the dollar value per ton of ore rises, enhancing deposit economics. Detailed mapping and exploration drilling of some of these deposits, particularly the Sanostee deposit and the deposits on the Ute Indian Reservation (northern San Juan Basin), are essential to fully evaluate the economic potential. Although, Zech et al. (1994) provided chemical analyses of the deposits on the Ute Indian Reservation, detailed chemical analyses of the remaining deposits in the San Juan Basin are essential to fully evaluate their resource potential in today's ever changing economic market.

INTRODUCTION

Beach-placer sandstone deposits are accumulations of heavy, resistant minerals (i.e. high specific gravity) that form on 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 (Bryan et al., 2007). Modern examples are found along the Atlantic Coast, USA (Koch, 1986; Carpenter and Carpenter, 1991), southeastern Australia (Roy, 1999), and Andhra Pradesh, India. Detrital heavy minerals comprise approximately 50-60% of the sandstones and typically consist of titanite, zircon, magnetite, ilmenite, monazite, apatite, rutile, xenotime, garnet, and allanite, among other minerals. Most of these minerals have a high specific gravity exceeding 4. 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 (Table 1; Chenoweth, 1957; Houston and Murphy, 1970, 1977). The beach-placer sandstones 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 Ti, Fe, Nb, Th, U, Zr, Sc, Y, and rare-earth elements (REE) are characteristic of these deposits. Collectively, the known deposits in the San Juan Basin (Fig. 1, Table 1) contain an estimated resource of 4.3 million metric tonnes of ore containing 12.8% TiO_2, 2.1% Zr, 15.5% Fe and less than 0.10% ThO_2 (Dow and Batty, 1961). 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 these elements, especially Ti and REE (including Y and Sc), 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, wind turbines, etc. As the demand for some of these elements increases because of increased demand and short supplies, the dollar value per ton of ore rises, enhancing deposit economics. Detailed mapping and exploration drilling of some of these deposits are essential to fully evaluate the economic potential.

The purposes of this paper are to: 1) describe the heavy mineral, beach-placer sandstone deposits in the San Juan Basin in New Mexico, 2) summarize the formation, tectonic setting, stratigraphy, and possible sources of these deposits, and 3) summarize their economic potential. This report presents unpublished geochemical analyses of selected deposits (Appendix 1) and builds upon previous reports that have been written describing these deposits and their formation. Published geochemical analyses are by Green et al. (1980) and Zech et al. (1994). Detailed mapping of selected deposits by Dow and Batty (1961), Bingler (1963, 1968), Zech et al. (1994), and others as cited, including the author (field work 1980-1983, 2009) is presented to illustrate the regional trend of the deposits.

METHODS OF STUDY

Data used in this report are compiled from a literature review, field investigations, and includes results previously unpublished by the author. Some of the deposits were mapped and samples were collected. Polished thin sections of selected samples were examined using standard petrographic techniques that included examination of the texture and mineralogy. The whole-rock geochemical data of selected samples collected by the author were determined at New Mexico Bureau of Geology and Mineral Resources (NMBGMR) laboratories by inductively coupled plasma atomic emission spectrometry (ICP). Other chemical

TABLE 1. Heavy mineral, beach-placer sandstone deposits in the San Juan Basin, New Mexico (U.S. Bureau of Mines and U.S. Atomic Energy files; Chenoweth, 1957; Dow and Batty, 1961; Houston and Murphy, 1970, 1977; Brookins, 1977; McLemore, 1983). New geologic mapping has occurred since the deposits were first described and, therefore, the host sandstone could be different than first described. The mine identification number (Mine id) is from the New Mexico Mines Database (McLemore et al., 2005a, b).

No. on Fig. 1	Mine id	County	Name (aliases)	Latitude	Longitude	Host formation
1	NMBE0005	Bernalillo	Herrera Ranch	35.187111	107.050083	Point Lookout Sandstone (?)
2	NMSA0049	Sandoval	Herrera Ranch	35.224111	107.082667	Gallup Sandstone
3	NMSA0028	Sandoval	B. P. Hovey Ranch (Torreon Wash)	35.659444	107.252639	Point Lookout Sandstone
4	NMMK0060	McKinley	Farr Ranch (Star Lake)	35.880167	107.434778	Pictured Cliffs Sandstone
4	NMMK0061	McKinley	Farr Ranch (Star Lake)	35.875139	107.461444	Pictured Cliffs Sandstone
4	NMMK0062	McKinley	Farr Ranch (Star Lake)	35.857444	107.443472	Pictured Cliffs Sandstone
4	NMMK0063	McKinley	Farr Ranch (Star Lake)	35.852611	107.438889	Pictured Cliffs Sandstone
5	NMMK0072	McKinley	Gallup (Defiance, Torrivio Anticline)	35.481639	108.870778	Gallup Sandstone
6	NMMK0108	McKinley	Miguel Creek Dome	35.546028	107.482889	Crevasse Canyon Formation-Dalton Sandstone Member
7	NMMK0261	McKinley	Standing Rock (Flat Top Hill)	35.745389	108.301667	Point Lookout Sandstone
8	NMRA0001	Rio Arriba	Airborne Anomaly 1 (Stinking Lake)	36.665	106.825417	Point Lookout Sandstone
8	NMRA0002	Rio Arriba	Airborne Anomaly 3 (Stinking Lake)	36.574028	106.793944	Point Lookout Sandstone
8	NMRA0003	Rio Arriba	Airborne Anomaly 2 (Stinking Lake)	36.662528	106.821278	Point Lookout Sandstone
8	NMSJ0002	San Juan	Airborne Anomaly 4 (Barker Dome)	36.892313	108.25757	Pictured Cliffs Sandstone
9	NMSJ0003	San Juan	Airborne Anomaly 5	36.772	108.545667	Point Lookout Sandstone
9	NMSJ0004	San Juan	Airborne Anomaly 6	36.826306	108.515417	Point Lookout Sandstone
9	NMSJ0005	San Juan	Airborne Anomaly 7	36.883444	108.470806	Point Lookout Sandstone
9	NMSJ0006	San Juan	Airborne Anomalies 8, 9	36.874116	108.4602032	Point Lookout Sandstone
9	NMSJ0007	San Juan	Airborne Anomalies 10, 11	36.8694862	108.453519	Point Lookout Sandstone
9	NMSJ0008	San Juan	Airborne Anomaly 12	36.86586	108.457431	Point Lookout Sandstone
9	NMSJ0009	San Juan	Airborne Anomaly 13, 14, 15	36.881206	108.4501582	Point Lookout Sandstone
9	NMSJ0010	San Juan	Airborne Anomaly 16, 17, 18	36.8915136	108.49564	Point Lookout Sandstone
9	NMSJ0011	San Juan	Airborne Anomaly 19, 20, FA1	36.904199	108.5125194	Point Lookout Sandstone
9	NMSJ0012	San Juan	Airborne Anomaly 21	36.9329319	108.5138095	Point Lookout Sandstone
9	NMSJ0013	San Juan	unknown	36.92975	108.506778	Point Lookout Sandstone
9	NMSJ0014	San Juan	Airborne Anomaly 22, 23 (Salt Creek Wash)	36.953889	108.530278	Point Lookout Sandstone
9	NMSJ0015	San Juan	unknown	36.951222	108.526472	Point Lookout Sandstone
9	NMSJ0016	San Juan	Airborne Anomaly 24	36.953639	108.551722	Point Lookout Sandstone
9	NMSJ0017	San Juan	Airborne Anomaly 32	36.955474	108.614891	Point Lookout Sandstone
9	NMSJ0018	San Juan	Airborne Anomaly 33	36.973486	108.614159	Point Lookout Sandstone
9	NMSJ0019	San Juan	Airborne Anomaly 34	36.957985	108.615112	Point Lookout Sandstone
9	NMSJ0020	San Juan	Airborne Anomaly 35	36.964092	108.614879	Point Lookout Sandstone
9	NMSJ0021	San Juan	Airborne Anomaly 36	36.8944436	108.521101	Point Lookout Sandstone
9	NMSJ0022	San Juan	Airborne Anomaly 37	36.9219833	108.5113143	Point Lookout Sandstone
9	NMSJ0023	San Juan	Airborne Anomaly 46	36.634045	108.577897	Point Lookout Sandstone
9	NMSJ0037	San Juan	Deposit 2	36.971746	108.559063	Point Lookout Sandstone
9	NMSJ0038	San Juan	Deposit X-Y	36.84282	108.456884	Point Lookout Sandstone
10	NMSJ0054	San Juan	Hogback (Elmer Davidson, Willie Davidson)	36.809722	108.516667	Point Lookout Sandstone
11	NMSJ0088	San Juan	Sanostee	36.44894	108.898049	Gallup Sandstone
12	NMSJ0095	San Juan	Toadlena	36.227892	108.867162	Gallup Sandstone

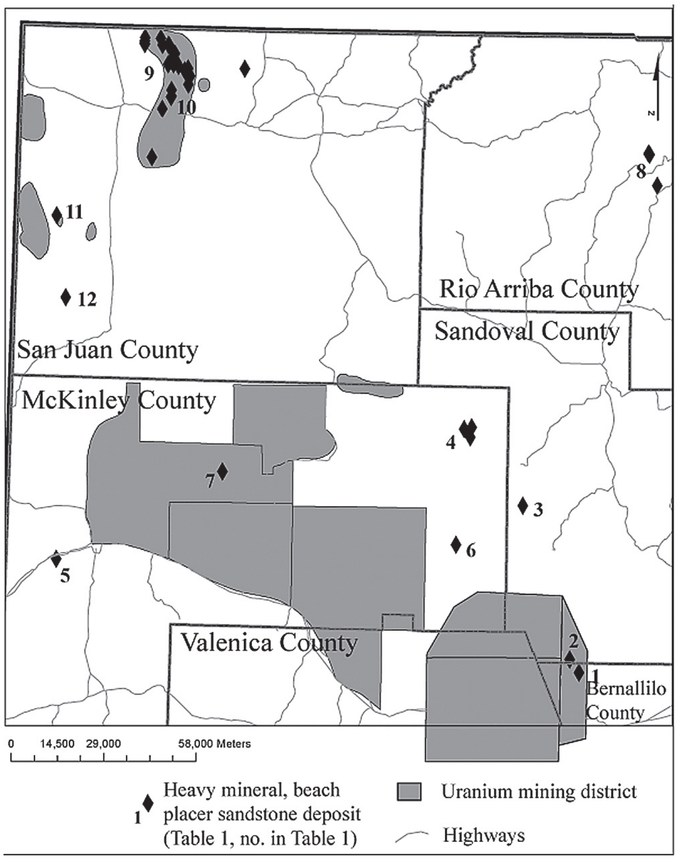

FIGURE 1. Location of Late Cretaceous heavy mineral, beach-placer sandstone deposits in the San Juan Basin, New Mexico. More detailed location of the Shiprock deposits (no. 9, 10) are in Figure 8.

analyses are from the literature, as cited. Selected chemical analyses are in Appendix 1 and the complete chemical analyses are in McLemore (2010). Laboratory methods and analytical precision are described in McLemore and Frey (2009) and references cited therein. Any resource or reserve data presented here are historical data and are provided for information purposes only and do not conform to Canadian National Instrument NI 43-101 requirements.

EVALUATION OF THE NURE DATA

A regional geochemical database of stream sediments exists for the state of New Mexico that was generated from reconnaissance surveys as part of the U.S. Department of Energy's National Uranium Resource Evaluation (NURE) program during 1974-1984 (McLemore and Chamberlin, 1986). The NURE data are typically arranged by 1x2-degree quadrangles, although the Grants uranium district was sampled and evaluated in greater detail. Parts of four 1x2-degree quadrangles cover the San Juan Basin: Shiprock, Gallup, Albuquerque, and Aztec. The main purposes of the NURE program were to provide an assessment of the nation's uranium resources and to identify areas favorable for uranium mineralization. The NURE data were not designed to reveal uranium or other mineral deposits, but if the NURE data are used with caution, the data can be used to identify areas of potential geochemical interest for further study. Ultimately, field examination of these identified areas must be conducted. Specific details of the statistical analysis methods, descriptive statistics for each element, and evaluation of the NURE data will be in a future report. Zumlot (2006) and Zumlot et al. (2009) also presented an evaluation of the NURE data for the entire state and used slightly different statistical techniques than used by the author in this report (explained in detail in McLemore, 2010).

NURE geochemical data aided in the exploration of modern beach-placer deposits in Georgia, North Carolina, and Virginia (Koch, 1986; Carpenter and Carpenter, 1991). However, preliminary examination of the NURE stream-sediment geochemical data in the San Juan Basin in areas of known heavy mineral, beach-placer sandstone deposits indicated no significant geochemical anomalies. That is probably explained by: 1) the deposits in New Mexico are much smaller than the large modern deposits along the Atlantic Ocean, 2) the sampling density in the San Juan Basin was not detailed enough to locate such small deposits, and 3) streams draining from the deposits in the San Juan Basin were not sampled. There are numerous single-element geochemical anomalies of Zr, Ti, REE, and Th scattered throughout the San Juan Basin that could be indicative of undiscovered heavy mineral, beach-placer sandstone deposits, but significant field examination is required to verify those anomalies, which is beyond the scope of this paper.

PREVIOUS INVESTIGATIONS

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 (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, 2000). Murphy (1956) described some of the deposits in these states and recommended additional investigation. Chenoweth (1957), Dow and Batty (1961), Overstreet (1967), and Brookins (1977) 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 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 the deposits (Appendix 1, McLemore, 2010). McLemore et al. (1988a, b) discussed the REE potential of beach-placer sandstone deposits. New geologic mapping has occurred since the deposits were first described and, therefore, the host sandstone could be different than first described, primarily because of the intertonguing nature of the transgressive-regressive sandstone units. Details of the Cretaceous nomenclature and depositional history are in cited references and elsewhere in this guidebook; Figure 2 summarizes the stratigraphic nomenclature of the Late Cretaceous rocks in the San Juan Basin.

GEOLOGIC 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 Artic Ocean.. Complex fluvial systems transported sediments from the volcanic and metamorphic sources in the Mogollon Highlands 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 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 in Australia (Roy, 1999). If beach-placer deposits formed in Late Cretaceous sand dunes in the San Juan Basin, they were not preserved.

DISTRIBUTION IN THE SAN JUAN BASIN

The majority of the beach-placer sandstone deposits in New Mexico are discontinuous, lenticular- or crescent-shaped, radioactive, well-cemented, medium-grained to very fine-grained, well sorted, and without cross-bedding (Figs. 3, 4, 5, 6). They are found in dark-colored sandstones, including olive-gray, rust-brown, brownish-black to maroon, and occasionally are called black-sandstone deposits. Host formations include the Gallup Sandstone, Dalton Sandstone Member of the Crevasse Canyon Formation, Point Lookout Sandstone, and Pictured Cliffs Sandstone (Fig. 2). Many of the Cretaceous shoreface sandstone beds containing beach-placer deposits either form the resistant caps

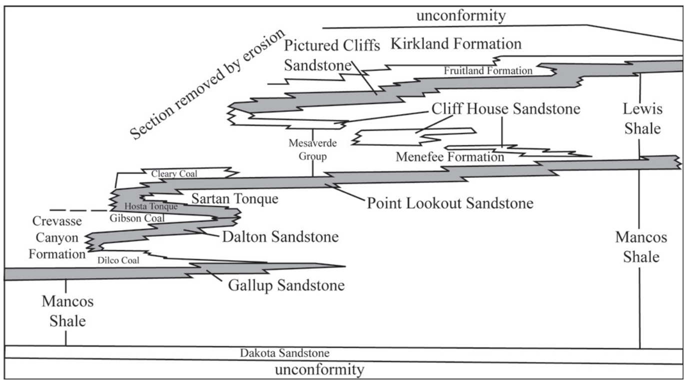

FIGURE 2. Stratigraphic framework and nomenclature of the Late Cretaceous sedimentary rocks in the San Juan Basin (simplified from Molenaar, 1989; Craigg et al., 1990; Fassett, 2000). Gray-shaded sandstone units are hosts of known beach-placer sandstone deposits in the San Juan Basin.

of mesas or are overlain by black shale and coal or Quaternary sedimentary deposits.

GALLUP SANDSTONE

The Gallup Sandstone is the oldest of the sandstone units hosting beach-placer sandstone deposits in the San Juan Basin (Fig. 2) and forms regressive beach deposits overlain by transgressive offshore-bar deposits (Campbell, 1971, 1979). Locally, the Gallup Sandstone is mapped as the Torrivio Member and an unnamed lower member (Millgate, 1991).

Gallup deposit, McKinley County

The Gallup (also known as Defiance or Torrivio Anticline) deposit, in section 32, T15N, R19W, west of Gallup and south of Interstate 40 (Fig. 1, 3, Table 1), is in an olive-green to dark-brown to gray, medium- to fine-grained, well to moderately sorted, heavy-mineral sandstone bed with rounded to subrounded grains and no cross bedding and lies on top of a white to buff, cross bedded, medium-grained sandstone bed in the Gallup Sandstone. The deposit trends N25°W intermittently for 457 m (Fig. 3), is less than 30 m wide, up to 1.2 m thick, and is overlain by black to gray shale and thin coal beds. The deposit contains monazite, ilmentite, rutile, brookite, anatase, leucoxene, magnetite, and zircon (Allen, 1956; Sun and Allen, 1957; Chenoweth, 1957; this report). A sample from the deposit (#2391) contained the highest REE concentrations of beach-placer sandstone samples analyzed, containing 4250 ppm La and 8375 ppm Ce (Appendix 1). Resources are estimated as 5400 metric tonnes containing 0.6% TiO_2 and 6.5% Fe (USBM files).

Sanostee deposit, San Juan County

The largest exposed beach-placer sandstone deposit in New Mexico is the Sanostee deposit, which lies along the top of a mesa northwest of Sanostee, NM on the Navajo Indian Reservation (Fig. 1, 4, Table 1; Bingler, 1963; Force, 2000). The Sanostee deposit is in an olive-green-gray to dark brown to black, medium- to fine-grained, well to moderately sorted, heavy-mineral sandstone bed with rounded to subrounded grains and no cross bedding that overlies a white to buff, cross bedded, medium-grained sandstone, with local rust staining within the Gallup Sandstone. This deposit formed in a regressive shoreface environment. The deposit trends N30°W, dips 5-10°W, is approximately 2400 m long (Fig. 4), 152-183 m wide, 1-4 m thick, and is overlain by black to gray shale. The deposit occurs in two separate zones forming a resistant, cliff-forming ledge along the mesa (Fig. 4; Force, 2000; V.T. McLemore, field mapping, 2010). Bingler (1963) described six discrete zones based upon exposure and stratigraphy. The deposit contains ilmentite, magnetite, hematite-ilmenite, zircon, tourmaline, garnet, hematite, staurolite, apatite, barite, sphene, and rutile (Bingler, 1963; Force, 2000; Force et al., 2001; this report). Only limited chemical analyses are available for this deposit (Appendix 1, McLemore, 2010), and additional sampling is required to fully characterize this deposit. Resources

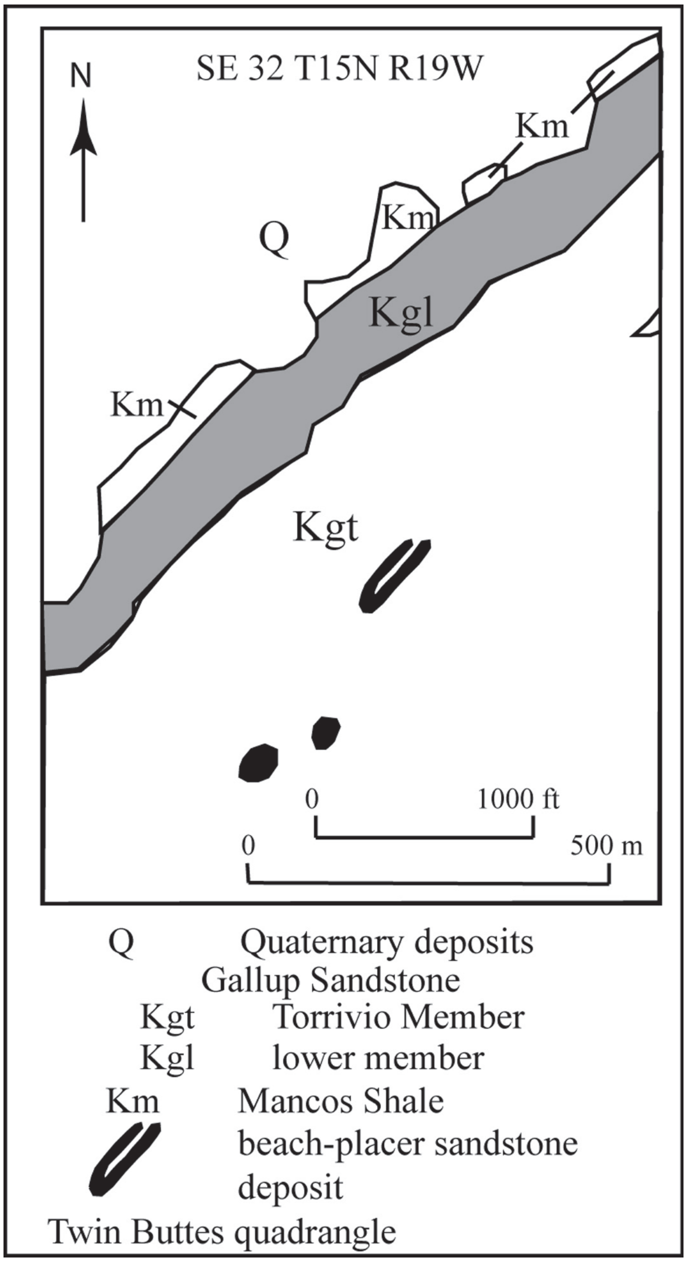

FIGURE 3. Geologic map of the Gallup beach-placer sandstone deposits. Mapping of the deposit was by V.T. McLemore in 2009, sedimentary geology simplified from Millgate (1991).

are estimated as 3.2 million metric tonnes containing 13.2% Fe, 15.6% TiO_2, 2.6% ZrO_2, and 0.12% ThO_2 (USBM files).

Toadlena, San Juan County (NMSJ0095)

The Toadlena deposit, near Toadlena, New Mexico also on the Navajo Indian Reservation (Fig. 1, Table 1), consists of olive-green to gray sandstone that is approximately 457 m long and 0.6-2.4 m thick, trends N20°E, and consists of ilmenite, magnetite, and monazite (Chenoweth, 1957; Archer, 1957). The host is the Gallup Sandstone exposed along the steeply dipping hogback. Dow and Batty (1961) reported a sample containing 0.4% TiO_2, 11% Fe, and 530 ppm Th. Resources are estimated as 2300 metric tonnes of 0.11% Fe, 0.4% TiO_2, and 0.06% ThO_2 (USBM files).

Herrera Ranch, Sandoval County

One of the Herrera Ranch deposits (also known as the Anaconda deposit) is within a bluff to gray sandstone bed belonging to the Gallup Sandstone and is found in section 31, T12N, R12W in the southeastern San Juan Basin (Fig. 1, Table 1; Chenoweth, 1957). It is approximately 0.3 m thick, 15 m wide, and 61 m long and trends N20°E. No chemical analyses are available for this deposit. The other Herrera Ranch deposit is in Point Lookout Sandstone.

Dalton Sandstone

Miguel Creek Dome, McKinley County

The Miguel Creek Dome deposits in section 8, T15N, R6W (Fig. 1, Table 1) are the only known deposits within the Dalton Sandstone member of the Crevasse Canyon Formation. The deposits consist of two small lenses within green-gray to olive-gray sandstone (Chenoweth, 1957). The largest deposit is 67 m long, 37 m wide, 0.5 m thick, trends N40°E, and consists of ilmenite, magnetite, quartz, zircon, and monazite. Only limited chemical analyses are available for this deposit (Appendix 1,

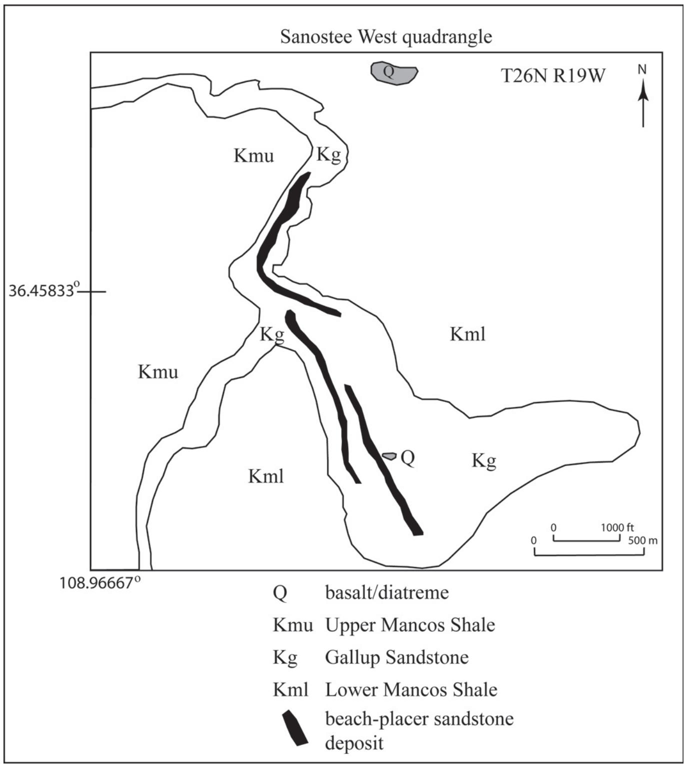

FIGURE 4. Geologic map of the Sanostee beach-placer sandstone deposits, in section 31, T26N, R19W. Mapping of the deposit was by V.T. McLemore in 2009, modified from Beaumont (1954), Dow and Batty (1961), Bingler (1963), and Force (2000).

McLemore, 2010), and additional sampling is required to fully characterize this deposit. Resources are estimated as approximately 610 metric tonnes of 0.4% ZrO_2, 4% TiO_2, 17.2% Fe and 0.03% ThO_2 (USBM files).

Point Lookout Sandstone

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 (12-127 m), and is a regressive sandstone (Hollenshead and Pritchard, 1961; Talbot 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. 2). The Point Lookout Sandstone was deposited in upper shoreface, foreshore, washover, and eolian environments (Zech, 1982; Zech et al., 1994). In the northern part of the San Juan Basin, the heavy mineral, beach-placer sandstone deposits are at the top of the Point Lookout Sandstone and trend N55-60°W (Figs. 2, 8).

Herrera Ranch, Bernalillo County

The second deposit on the Herrera Ranch is in section 16, T11N, R2W (Fig. 1, Table 1) and is in brown-gray sandstone belonging to the Point Lookout Sandstone. The deposit is small, less than 1 m thick and only a few tens of meters long. No chemical analyses are available for this deposit.

B. P. Hovey Ranch, Sandoval County

The P.B. Hovey Ranch deposit (also known as the Torreon Wash deposit) is in section 34, T17W, R4W (Fig. 1, 5, Table 1). The deposit is in brown- to olive-gray, medium grained, well to moderately sorted sandstone and is approximately 100 m long and 0.6-1.5 m thick (Fig. 5). There are two zones of beach-placer deposits at the B. P. Hovey Ranch locality (McLemore, 1983, fig. 26). Drilling suggests that this deposit continues to the northwest (Chenoweth, 1957). Only limited chemical analyses are available for this deposit (Appendix 1, McLemore, 2010), and additional sampling is required to fully characterize this deposit.

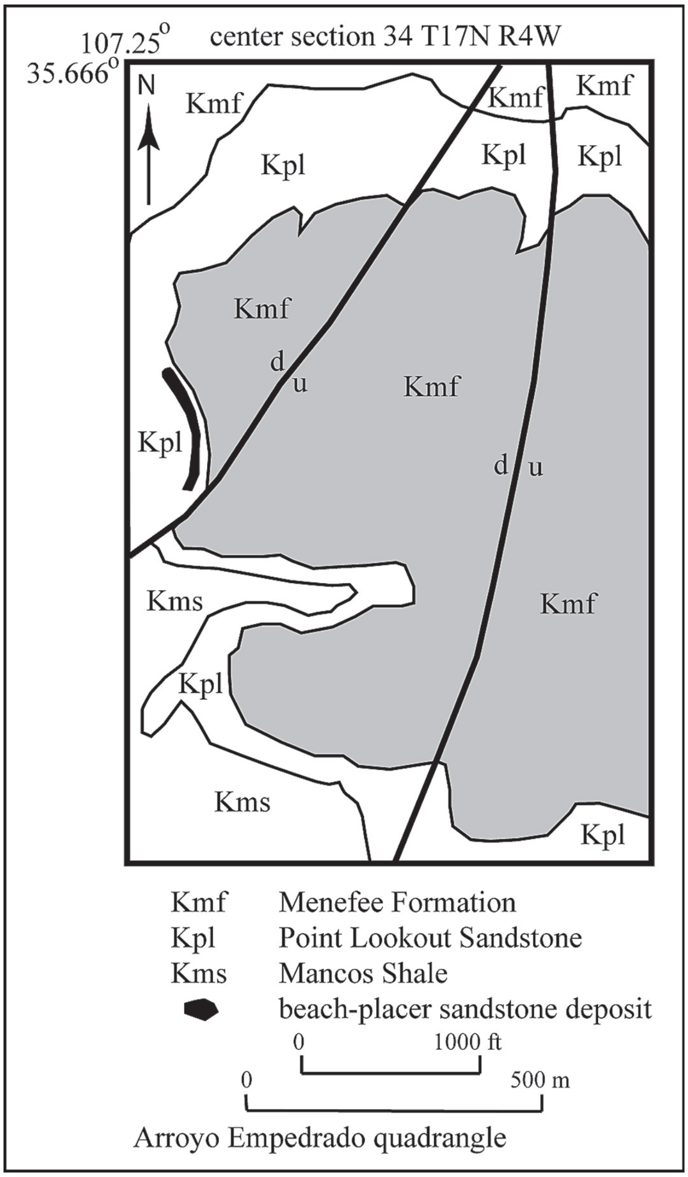

FIGURE 5. Geologic map of the B. P. Hovey beach-placer sandstone deposit. Mapping of the deposit was by V.T. McLemore in 1981, sedimentary geology modified from Tabet and Frost (1979).

Standing Rock (Flat Top Hill) deposit, McKinley County

The Standing Rock (also known as Flat Top Hill) deposit, in section 35, T18N, R14W, also on the Navajo Indian Reservation (Fig. 1, 6, Table 1), is in a dark orange-brown to yellow to black, medium- to fine-grained, well to moderately sorted, heavy-mineral sandstone lens with no cross bedding resting on top of a lower sandstone bed in the Point Lookout Sandstone. It caps the mesa top of Flat Top Hill (Fig. 6; Chenoweth, 1957; Kirk and Sullivan, 1987) and overlies a white to buff, cross bedded, medium-grained sandstone bed. It is as much as 1.5 m thick, 30 m wide, and consists of at least 2 lenses striking N50°W for approximately 1500 m. Calcite veining cuts the sandstone deposit locally. The deposit contains monazite, ilmenite, anatase, leucoxene, rutile, zircon, and magnetite. Only limited chemical analyses are available for this deposit (Appendix 1, McLemore, 2010), and additional sampling is required to fully characterize this deposit. Resources are estimated as 635,000 metric tonnes of 4.2% TiO_2, 0.35% ZrO_2 and 0.06% ThO_2 (USBM files).

Hogback, San Juan County

The Hogback deposit in section 15, T30N, R16W (Fig. 1, 7, Table 1), is the only deposit to have yielded production. In 1954, a test shipment of 8 short tons of ore was shipped to a AEC ore-buying station by Willie Davidson (McLemore, 1983). This shipment yielded 3 lbs of 0.02% U_3O_8 and 23 lbs of V_2O_5 The deposit is in an olive-green-gray to dark brown to black, medium- to fine-grained, well to moderately sorted, heavy-mineral sandstone lens

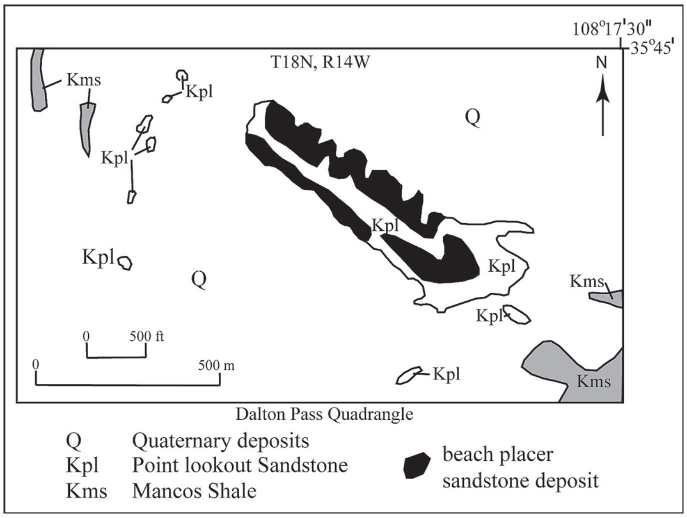

FIGURE 6. Geologic map of the Standing Rock beach-placer sandstone deposit in section 35, T18N, R14W. Mapping of the deposit was by V.T. McLemore in 2009, sedimentary geology modified from Kirk and Sullivan (1987).

with no cross bedding within the Point Lookout Sandstone. The deposit dips 10°E, is overlain by black to gray shale and coal, and overlies a white to buff, cross- bedded, medium-grained sandstone bed (Fig. 7). The deposit is approximately 0.3-0.6 m thick, 91 m long, and contains ilmentite, magnetite, and zircon. At least four additional similar deposits are found in the Point Lookout Sandstone along the Hogback area west of Farmington (Chenoweth, 1957; Strobell et al., 1980). Only limited chemical analyses are available for this deposit (Appendix 1, McLemore, 2010), and additional sampling is required to fully characterize it.

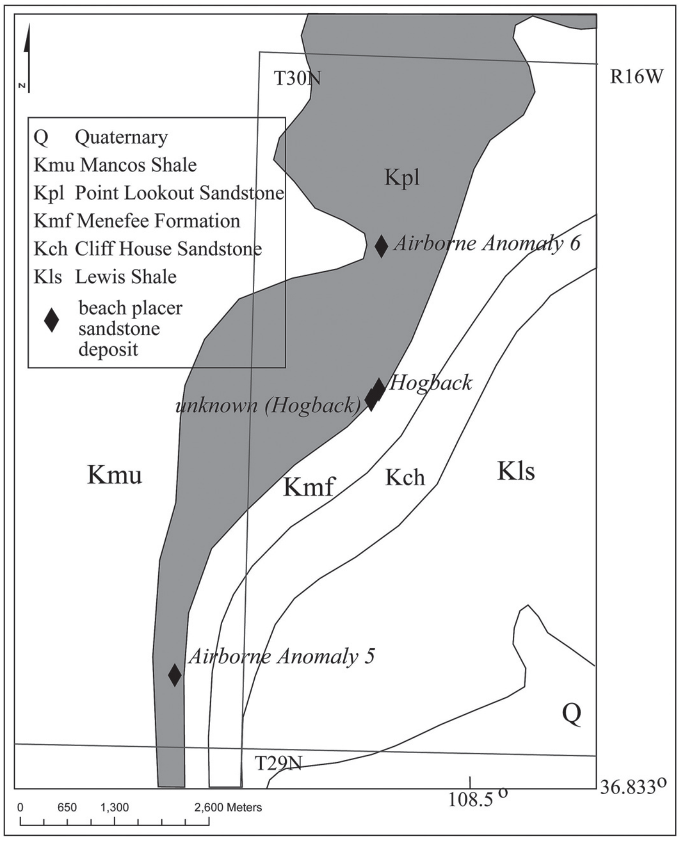

FIGURE 7. Geologic map of the Hogback beach-placer sandstone deposit. Mapping of the deposit was by V.T. McLemore in 2009, sedimentary geology modified from Strobell et al. (1980) and New Mexico Bureau of Geology and Mineral Resources (2003).

Ute Indian Reservation (Mesa Verde)

Beach-placer sandstone deposits are found in 29 separate localities in the upper Point Lookout Sandstone in and adjacent to the Ute Indian Reservation in southern Colorado and northern New Mexico (Fig. 8, Table 1; Chenoweth, 1957; Dow and Batty, 1961; Zech et al., 1994). This is the largest cluster of closely spaced deposits in the San Juan Basin, although most are small tonnage and grade or are covered by recent dune sands or talus. The deposits are purplish-gray and typically trend N55-60ºW, are up to 2.3 m thick, and are a few tens of meters to more than a kilometer long (Zech et al., 1994). Detailed chemical analyses are from Zech et al. (1994) are in Appendix 1.

Airborne Anomalies 1-3 (Stinking Lake), Rio Arriba County

The Airborne Anomalies 1-3 deposits in the Stinking Lake area are in section 3, T28N, R1E and section 2, T27N, R1E, on

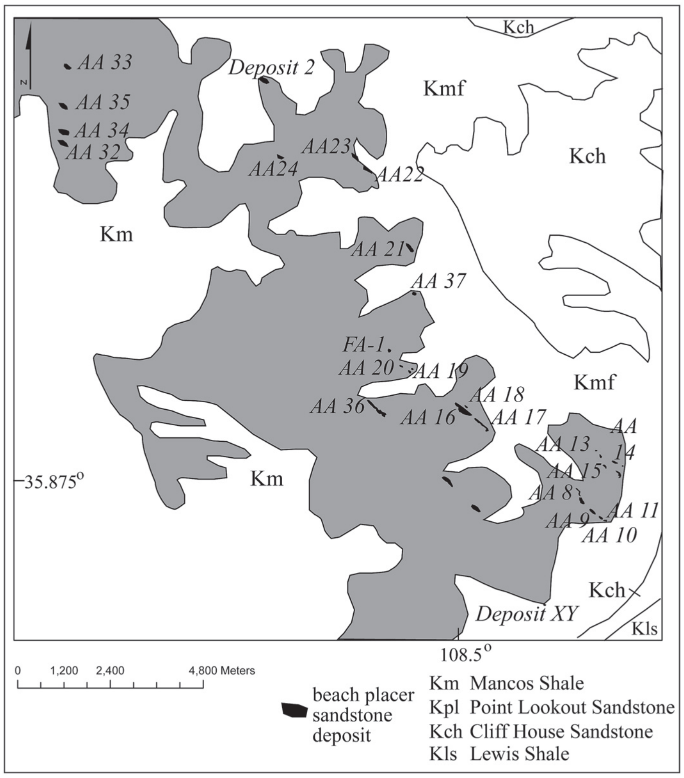

FIGURE 8. Geologic map of the beach-placer sandstone deposits on the Ute Indian Reservation and adjacent area (modified from AEC records; Strobell et al., 1980; Zech et al., 1994; New Mexico Bureau of Geology and Mineral Resources, 2003).

the Jicarilla Apache Reservation in the eastern San Juan Basin (Fig. 1, Table 1) and are in the Point Lookout Sandstone (Bingler, 1968). The original naming of these deposits as airborne anomalies followed by a number is as designated by the airborne survey and the field reconnaissance reports and is maintained in this and previous reports. The deposits are lenses, approximately 213-914 m long and 0-2.4 m thick, and are found at the top of a 3.7-m thick, gray to yellow-white to reddish-brown, fine- to medium-grained, cross-bedded quartz sandstone (Bingler, 1968). The heavy mineral sandstone is reddish-purple to olive-brown, well cemented, and contains iron oxide minerals, leucoxene, zircon, tourmaline, rutile, magnetite, and ilmenite (Bingler, 1968). No chemical analyses are available for this deposit. Bingler (1968) estimates a potential resource of approximately 4.5 million metric tonnes containing up to 5.7% TiO_2.

Pictured Cliffs Sandstone

The Pictured Cliffs Sandstone is a regressive shoreface sandstone that is up to 30 m thick and outcrops nearly around the entire periphery of the San Juan Basin (Fassett, 2000). The Pictured Cliffs conformably overlies the marine Lewis Shale and is overlain by the coal-bearing Fruitland Formation.

Farr Ranch (Star Lake), McKinley County

The Farr Ranch deposits, in sections 13, 14, 15, 23, 25, and 26, T19N, R6W (Fig. 1, Table 1), are in the Pictured Cliffs Sandstone, which consists of an upper zone of thick beds of yellow-gray to gray-orange, cross-bedded, fine- to medium-grained, well sorted friable sandstone beds overlying a lower zone of alternating thin beds of yellow-brown to brown, fine-grained, sandstone to siltstone and gray to dark-gray shale (Scott et al., 1980). The heavy mineral, beach-placer sandstones are found in several beds forming low bluffs, up to 18 m thick, trending N60°W, and contain U, Th, REE, Ti, Fe, and Zn. One sample contained 10.23% TiO_2 and 12.98% Fe_2O_3 (Appendix 1). The largest deposit is approximately 1066 m long and 46 m wide (Murphy, 1956).

Barker Dome, San Juan Basin

The Barker Dome deposits (also known as Airborne Anomaly 4), section 13, T31N, R14W (Fig. 1, Table 1) are in brown-gray Pictured Cliffs Sandstone. These deposits are less than 1 m thick and a few tens of meters long (Chenoweth, 1957). No chemical analyses are available for this deposit.

GEOCHEMISTRY

Chemical analyses of selected beach-placer deposits are in Appendix 1; complete whole-rock chemical analyses are in McLemore (2010) and include new analyses as well as analyses reported in the literature. Descriptive statistics are in Table 2, including ranges in selected elements. Ti, Fe, Cr, Nb, Th, U, Zr, Sc, and REE are found in high concentrations in these deposits. Pierson correlation coefficients indicate strong correlations

TABLE 2. Descriptive statistics and crustal abundance (Rudnick and Gao, 2005) of selected geochemical analyses of selected heavy mineral, beach-placer sandstone deposits in the San Juan Basin, New Mexico. Selected chemical analyses are in Appendix 1 and complete chemical analyses are in McLemore (2010). Elements are in parts per million, except for TiO_2 and FeOT (total iron reported as FeO) which are in percent.

	Cases	Mean	Standard.deviation	Minimum	Maximum	Abundance in the upper crust (ppm)
TiO_2%	49	5.67	5.30	0.17	22.5	0.64
FeOT%	49	16.12	10.42	1.15	34.91	5.04
Ag	35	15.13	5.77	1.5	23	53
Au	35	1.06	1.88	0.011	7	1.5
Ba	35	546.66	304.34	200	1302	628
Cr	35	597.40	454.50	12	1600	92
Nb	35	146.94	250.18	2	1490	12
Ni	35	80.11	30.91	14	108	47
Pb	36	76.17	68.96	2	243	17
Th	50	319.28	377.17	6.3	1983	10.5
U	38	47.98	56.30	1.6	331.4	2.7
Y	39	194.05	292.25	6	1795	21
Zn	34	335.21	163.68	2	570	67
Zr	43	12401.10	10635.60	150	31200	193
La	39	625.51	815.21	25	4250	31
Ce	38	1020.05	1383.03	2	8375	63
Sm	35	92.72	137.93	3.2	637	4.7
Eu	35	8.54	3.87	1	15	1.0
Tb	31	6.70	5.22	0.6	19	0.7
Yb	35	38.33	40.62	2	225	1.96
Lu	35	4.65	3.64	0.04	14	0.31

(Table 3) between TiO_2, Cr, Nb, Th, Y, Zr, and REE (Fig. 9), which is consistent with the known mineralogy of the deposits, predominantly reflecting ilmenite, monazite, zircon, and other heavy minerals. Many of the beach-placer deposits likely contain monazite, since they are all radioactive and monazite is the primary radioactive mineral. The REE plots exhibit light-REE chondrite-normalized enriched patterns, typically with negative Eu anomalies (Fig. 10).

POTENTIAL SOURCE TERRIANS

The whole-rock geochemical compositions of the beach-placer deposits are consistent with a granitic and/or metamorphic source terrain. Proterozoic granitic rocks, including syenites are exposed in the Zuni Mountains on the southern edge of the San Juan Basin (Goddard, 1966; McLemore and Mckee, 1989; Strickland et al., 2003) and could be a source if exposed during the Cretaceous. Dickinson and Gehrels (2009) determined the ages of detrital zircons found in Jurassic sedimentary rocks in the San Juan Basin and found that most of these detrital zircons were from basement rocks older than 285 Ma. Some researchers have suggested that Jurassic arc volcanism formed the Mogollon Highlands, south and west of the San Juan Basin, and this highland was the source of the Grants uranium in the Jurassic Morrison Formation (Fig. 11). This volcanic highland persisted into the Cretaceous and very well could have been a source of the heavy minerals in the beach-placer deposits in the San Juan Basin. Recycling of older sediments is likely. Detailed chemical analyses of the heavy minerals, such as ilmenite and zircon, within the beach-placer sandstone deposits are one method of determining the source of those minerals (Darby, 1984; Lloyd et al., 2005; McLimans et al., 2005). U-Pb dates of detrital zircons also aid in defining the source (Dickinson and Gehrels, 2009).

ORIGIN OF BEACH-PLACER SANDSTONE DEPOSITS

The Cretaceous heavy mineral, beach-placer sandstone deposits discussed herein have many physical and chemical characteris-

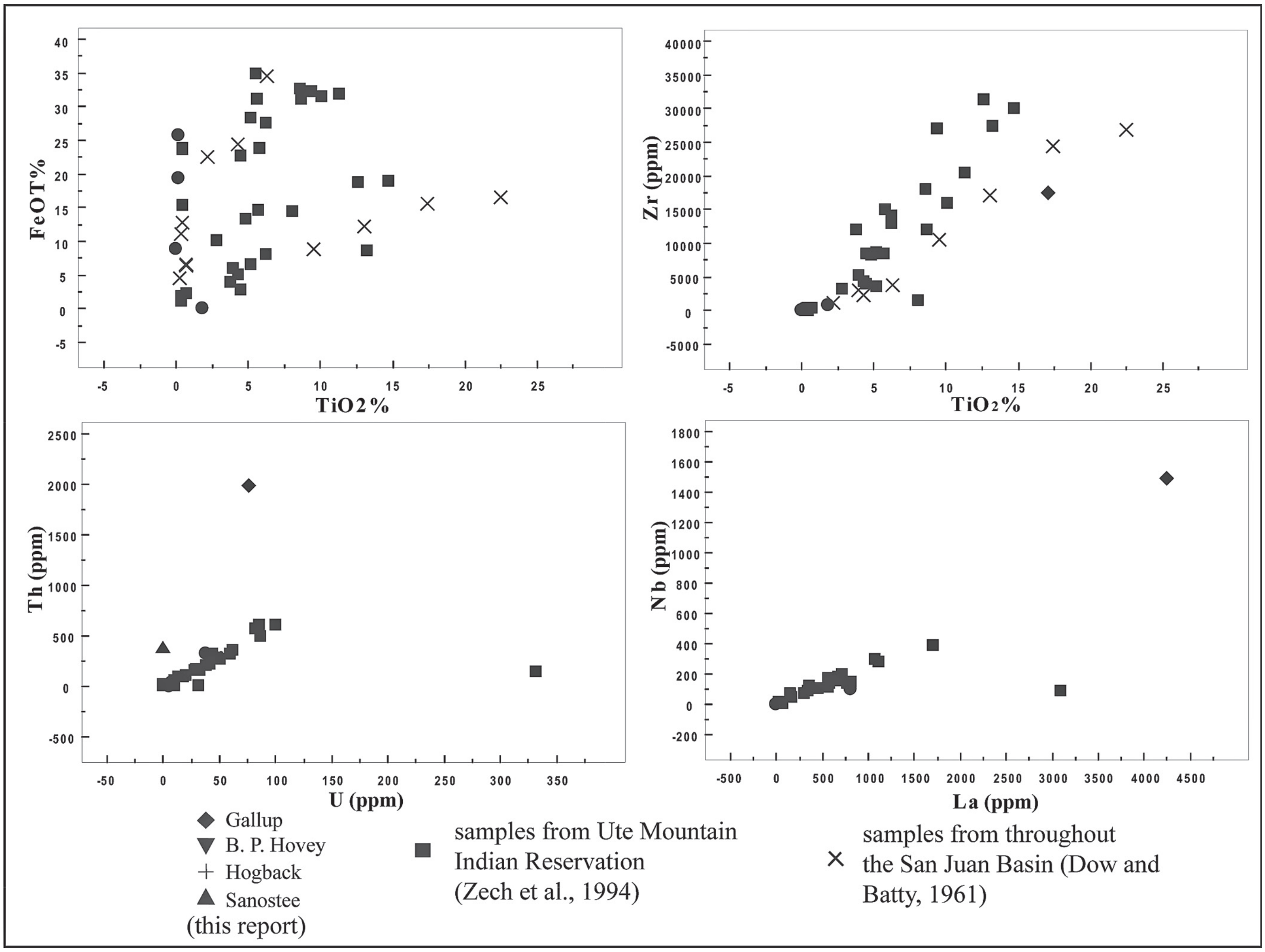

FIGURE 9. Scatter plots of chemical analyses of selected beach-placer deposits, San Juan Basin, New Mexico. Chemical analyses are in Appendix 1 and McLemore (2010) and correlation coefficients are in Table 3.

TABLE 3. Pierson correlation coefficients for selected geochemical analyses of beach-placer sandstone deposits, San Juan Basin, New Mexico. Chemical analyses are in Appendix 1. Elements are in parts per million, except for TiO_2 and FeOT (total iron reported as FeO) which are in percent.

	TiO_2	FeOT	Ag	Au	Ba	Cr	Nb	Ni	Pb	Th	U	Y	Zn	Zr	La	Ce
TiO_2	1.00															
FeOT	0.29	1.00														
Ag	0.37	0.11	1.00													
Au	0.09	0.26	0.00	1.00												
Ba	0.02	0.39	-0.15	0.07	1.00											
Cr	0.94	0.46	0.46	0.20	0.15	1.00										
Nb	0.72	0.23	0.25	0.04	-0.04	0.88	1.00									
Ni	0.35	-0.18	0.60	0.02	0.02	0.47	0.37	1.00								
Pb	0.86	0.65	0.34	0.17	0.18	0.86	0.54	0.28	1.00							
Th	0.78	0.11	0.16	-0.01	-0.04	0.80	0.97	0.35	0.64	1.00						
U	0.37	0.45	0.14	-0.13	0.14	0.31	0.19	0.05	0.40	0.24	1.00					
Y	0.72	0.19	0.15	-0.11	0.02	0.74	0.98	0.35	0.55	0.97	0.21	1.00				
Zn	0.13	-0.23	0.30	-0.28	-0.06	0.21	0.17	0.65	0.06	0.15	-0.03	0.14	1.00			
Zr	0.47	0.00	0.27	-0.15	-0.02	0.37	0.21	0.30	0.46	0.35	0.12	0.23	0.28	1.00		
La	0.65	0.02	0.16	0.14	-0.07	0.50	0.83	0.33	0.46	0.81	0.15	0.82	-0.02	0.16	1.00	
Ce	0.76	0.23	0.18	-0.01	-0.08	0.82	0.99	0.36	0.59	0.99	0.23	0.98	0.17	0.25	0.83	1.00

tics that are similar to modern beach-placers, including host rock, mineralogy, chemistry, and depositional environment (Houston and Murphy, 1970, 1977; Zech et al., 1994; Roy, 1999). These deposits formed by gravitational settling of the heavy minerals during wave action and currents that form beaches and offshore sand bars (Fig. 12; Houston and Murphy, 1970, 1977; Zech et al., 1994; Roy, 1999). 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 kilometers. Once the shoreface sandstone deposits are deposited, they are covered by continental deposits, which preserves 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 30 m 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. An idealized cross-section of the formation of beach-placer sandstone deposits in the San Juan Basin is in Figure 12 (Houston and Murphy, 1970, 1977). Destruction and reworking of older beach-placer deposits can occur only until they are covered by continental deposits.

MINERAL RESOURCE POTENTIAL

Many beach-placer sandstone deposits in the San Juan Basin contain high concentrations of Ti, Zr, REE, U, Th, Nb, Ta, Fe, Sc, Y, and other elements (Table 2, Appendix 1). Selected geochemical analyses are in Appendix 1 and McLemore (2010); maximum values for selected elements are in Table 2. Many of the deposits are on Indian reservation land. Additional deposits probably remain undiscovered in the San Juan Basin; at least three drill holes are suspected of having similar deposits (Chenoweth, 1957).

Titanium-bearing minerals (ilmenite, rutile, leucoxene) are the more important economic minerals in these heavy mineral, beach-placer sandstone deposits and TiO_2 is used in pigments (i.e. coatings and paints, plastics, cosmetics, textiles, glazes, etc.), metal alloys, and other applications. A titanium resource typically contains 1% or more ilmenite or rutile at recoverable grain size, typically in unconsolidated deposits (Force, 2000). Zirconium, REE, and Fe could be by-product minerals. Titanium is found in the San Juan Basin deposits in ilmenite, titanomagnetite, titanohematite, rutile, anatase, and brookite**.** Much of the ilmenite is either altered partially to hematite or is in solid solution series with hematite, which complicates processing (Force et al., 2001). Titanium varies in concentration from 16% to 32% in the San Juan Basin deposits (Appendix 1; Chenoweth, 1957; Zech et al., 1994). Force (2000) estimated the contained titanium resource of the Sanostee deposit as 700,000 metric tonnes of Ti ore and does not consider any other deposit in New Mexico to have any resource potential because of small size and low grade. However, drilling of these deposits is needed to fully evaluate their potential, considering today's economic market.

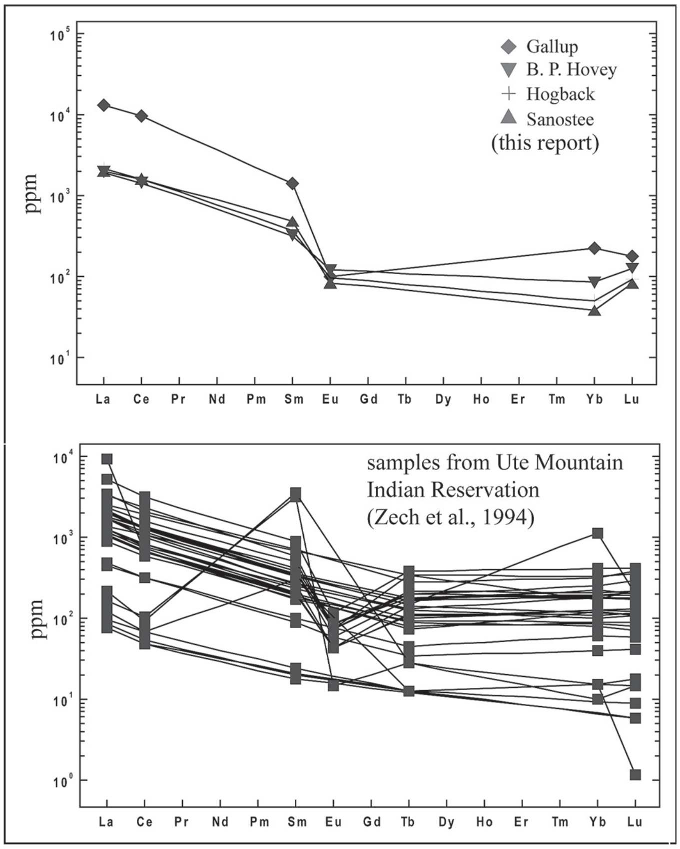

FIGURE 10. Chondrite-normalized REE plot of selected beach-placer deposits, San Juan Basin, New Mexico. Chemical analyses are in Appendix 1 and descriptive statistics are in Table 2. Chondrite values are from Haskins et al. (1968).

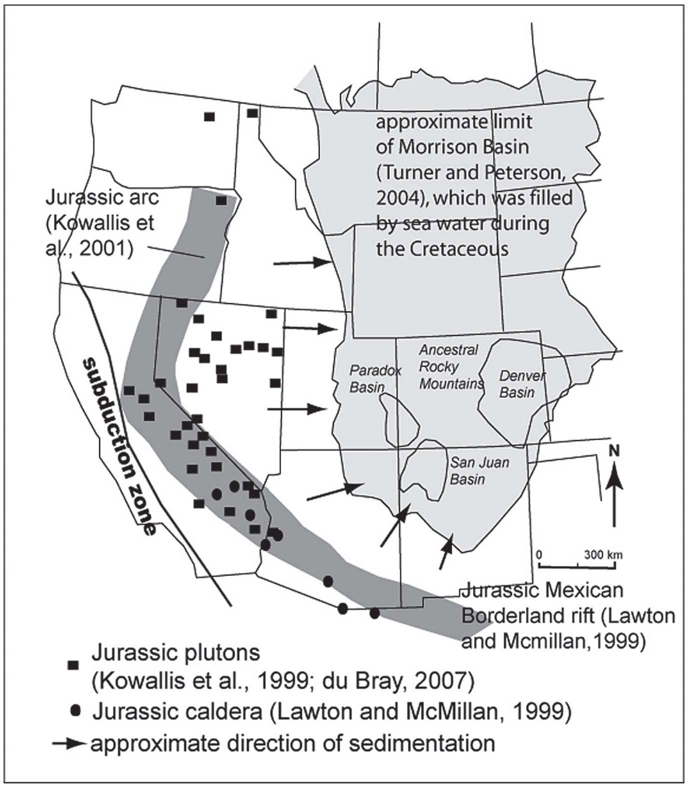

FIGURE 11. Approximate location of the Jurassic arc in relation to the Morrison Basin. This arc provided a highland consisting of granitic rocks that could have been a source for the Cretaceous beach-placer sandstone deposits in the San Juan Basin. Modified from Lawton and McMillan (1999), Kowallis et al. (1999, 2001), Turner and Peterson (2004) and du Bray (2007).

Zirconium is another potentially important economic element and is mostly found in zircon and, locally ilmenite. It is used in abrasives, ceramics, refractories, foundry applications, welding rod coatings, nuclear fuel industry applications, and other applications. Most of the deposits in the San Juan Basin contain zircon, which could be recovered for some applications only as a by-product. Impurities in zircon that could be recovered include Th, U, REE, and hafnium.

Rare earth elements (REE) include the 15 lanthanide elements (atomic number 57-71), yttrium (Y, atomic number 39), and scandium (Sc). REE are lithophile elements (or elements enriched in the crust) that have similar physical and chemical properties, and, therefore, occur together in nature. REE (including Y and Sc) are increasingly becoming more important in our technological society and are used in many of our electronic devices. The U.S. once produced enough REE for U.S. consumption, but since 1999 more than 90% of the REE required by U.S. industry have been imported from China. However, the projected increase in demand for REE in China, India, the United States, and other countries could result in increased exploration and ultimate production from future deposits in the U.S. and elsewhere. Furthermore, individual REE of high purity and mixtures of specific REE are becoming more economically important. Recently, the Chinese government announced that it is examining the economic feasibility of continuing to export REE from their deposits. Modern beach-placer sand deposits in Australia, India, South Africa, and the U.S. contain 0.1-2% monazite and are mined for REE (Morteani, 1991). In the San Juan Basin deposits, the REE are mostly found in monazite, although apatite, zircon, sphene, xenotime, allanite, and epidote also contain minor amounts of REE. However, the grades and tonnages of the San Juan Basin deposits are currently too low for commercial deposits (Table 2), but the REE could be recovered as by-products, especially if the

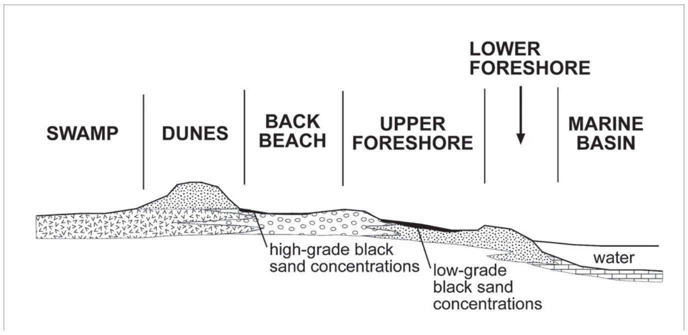

FIGURE 12. Idealized cross-section of formation of beach-placer sandstone deposits (Houston and Murphy, 1970, 1977).

deposits contain higher concentrations of a specific high-value REE (McLemore, 2010).

Uranium and Th are typically found in anomalously high concentrations in heavy mineral, beach-placer sandstone deposits (Table 2), but the concentrations are not of economic values today. Most of the U and Th in the San Juan Basin deposits are in zircon and monazite, although U and Th also are found in apatite and iron oxide minerals (Zech et al., 1994). Uranium is used mostly as fuel for nuclear power plants and, if the technology is developed, Th also could be become commercially viable as a fuel for nuclear power plants.

Niobium and Ta also are found in some of these deposits and could be recovered as a by-product. Gold was found in small amounts in the samples reported by Zech et al. (1994) and could be economic as a by-product. Although Zn is found in high concentrations in the samples reported by Zech et al. (1994), probably in magnetite and other iron-oxide minerals, the values are not of economic importance. Chromium is found in high concentrations, probably in ilmenite and magnetite. High Cr concentrations can adversely affect the milling process (Zech et al., 1994). Scandium is found in elevated concentrations, which could be recovered only as a by-product of other production. Garnet is found in many of the deposits, but the garnet is generally too small in grain size and in low concentrations to be considered economic.

CONCLUDING REMARKS

It is unlikely that any of the heavy mineral, beach-placer sandstone deposits in the San Juan Basin will be mined in the near future because of small tonnage, low grades, high degree of cementation through lithification, high iron content, and distance to processing plants and markets. However, as the demand for some of these elements increases because of increased demand and short supplies, the dollar value per ton of ore may rise, enhancing deposit economics. Mapping and exploration drilling of some of these deposits, especially the Sanostee deposit and the deposits on the Ute Mountain Ute Indian Reservation in the northern San Juan Basin could be warranted to fully evaluate the economic potential. Ultimately, economic potential will most likely depend upon production of more than one commodity. Not only do these deposits represent potential future economic resources, they also help define local depositional trends of the Cretaceous beaches at the time of deposition. Potential sources of these deposits include Proterozoic granitic and metamorphic rocks, such as those found in the Zuni Mountains, the Jurassic arc volcanism and magmatism forming the Mogollon Highlands to the south and west, and recycling of older sediments.

FUTURE WORK

Detailed microprobe analyses of monazite, apatite, zircon, and ilmenite can aid in delineation of the source terrain. Although, Zech et al. (1994) provided chemical analyses of the deposits in the Ute Mountain Indian Reservation, detailed chemical analyses of the remaining deposits in the San Juan Basin are essential to fully evaluate their resource potential, especially of the Sanostee deposit. Age determinations of heavy minerals within the deposits, such as zircon and monazite, also will aid in defining their source area. Preliminary examination of the NURE stream-sediment data revealed numerous single-element geochemical anomalies of Zr, Ti, REE, Sc, and Th scattered throughout the San Juan Basin; these areas need to be examined and sampled. Chenoweth (1957) identified three wells drilled for oil or gas with gamma anomalies in the Cretaceous sandstones, suggesting that these could be buried heavy mineral, beach-placer sandstone deposits; detailed examination of geophysical logs of wells could locate additional deposits.

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APPENDIX 1. Selected chemical analyses of heavy mineral, beach-placer sandstone deposits in the San Juan Basin, New Mexico. Complete whole-rock chemical analyses are in McLemore (2010). TiO_2 and FeOT (total iron reported as FeO) are in percent (%) and the remaining elements are in parts per million. Sample numbers are identified in Figures 3-8 or in the text.

Sample Number	TiO_2%	FeOT%	Ag	Au	Ba	Co	Cr	Nb	Ni	Sc	Th	U	Y	Zn	Zr
MCA101	1.83	>25	<1	<10	420	73	140		52	24	31.3	8.44	35		730
MCA507	0.17	25.73	<1	<10	1300	15	12	<25	14	15	<3	6.08	34	<50	230
MCA508	>2.5	8.75	1.5	<10	440	59	320	100	89	44	321	38.3	300	300	>1000
MCA509	0.22	19.3	<1	<10	930	14	17	<25	14	12	8.99	3.23	19	<50	150
2391	17.1							1490			1983	76	1795		17454
2741													144		
2740		13.2									380	<5	98		
2745		18.4									280	52	107		
AA-8	9.36	32.22	14	0.011	540	81	890	147	96	42.4	602	100	300	<260	26900
AA-9	14.71	18.88	<10	0.02	690	50	1500	385	<45	92.7	608	85.3	511	500	30000
AA-10-1	0.69	2.27	<2	0.02	720	8	91	11	<20	9.3	11	3	19	<100	430
AA-10-2	0.37	1.87	<2	0.13	340	<5	77	6	<20	3.7	6.6	1.6	10	<100	<200
AA-10-3	0.4	1.58	<2	0.16	740	7	66	6	<20	3.8	7.2	2.1	10	<100	<200
AA-10-4	4.51	2.75	<2	0.036	290	55	400	71	37	24.6	94.3	14	72	120	3900
AA-10-5	0.41	1.15	<2	0.14	410	<5	96	5	<20	3.6	6.3	1.6	20	<100	<200
AA-10-6	4.34	5	<6	<0.005	410	36	520	88	<29	35.4	88.5	15	112	180	4200
AA-10-7	4.86	13.25	<7	<0.007	290	53	700	108	<33	43.5	161	28.7	141	330	8200
AA-10-8	5.15	6.45	<2	0.026	200	9	400	120	<20	33.9	94.6	18	107	<100	3600
AA-10-9	11.29	31.87	<9	<0.009	<190	86	1600	192	<43	55.2	353	62.4	291	320	20500
AA-10-10	10.09	31.43	<11	<0.01	320	130	1300	171	<50	50.8	268	51	6	360	16000
AA-10-11	2.84	10.11	<2	0.02	410	29	350	47	32	18	62.4	10	46	140	3100
AA-10-12	13.22	8.57	<10	0.014	470	<11	1200	278	<46	59.1	567	81.7	398	450	27400
AA-10-13	6.27	27.56	<5	0.089	790	40	840	156	<22	42.7	223	41.8	242	180	13000
AA-11	0.48	23.51	7	0.04	290	35	100	3	30	12	9.5	10	17	<100	430
AA-13	8.06	14.5	<5	0.059	350	<5	1000	178	<21	53.9	284.7	41.5	249	<100	1400
AA-14	4.47	22.69	10	<0.005	210	30	330	103	28	40	162	32.2	150	180	8400
AA-16	12.67	18.65	12	0.029	450	92	1300	299	87	71.6	494	87	417	360	31200
AA-17-1	0.45	15.42	<2	0.011	510	21	150	3	<20	16	7.1	<3.3	15	<100	390
AA-17-2	8.68	31.02	<8	0.019	410	90	1000	146	67	49.1	210	38	193	320	12000
AA-17-3	5.56	34.91	<6	0.012	<120	50	750	90	<28	29.9	24.8	<3	107	<100	8400
AA-17-4	5.71	14.61	<7	0.014	890	170	740	102	100	30.3	174	30.1	180	<230	8400
AA-17-5	3.98	5.89	<5	0.013	370	12	460	72	<22	30	112	20	106	160	5200
AA-19	5.6	31.09	<2	0.09	650	66	490	106	49	34	150	331	139	160	8500
AA-20	8.57	32.67	<6	0.038	290	77	750	139	48	47.2	318	59.4	250	250	18000
AA-21	3.79	3.88	<5	0.078	270	9	530	136	<23	30.6	325	43.4	261	<100	12000
AA-36-NW	5.83	23.71	<6	0.085	870	88	1200	112	<25	50.5	284	48.1	199	570	15000
AA-36-SE	5.16	28.21	<4	<0.004	500	66	780	101	<20	34.4	163	28.9	146	240	8600
AA-37	6.25	7.95	<6	0.059	360	20	640	162	<29	43.7	255	41.5	300	270	14000
FA-1	0.51	23.76	<2	0.015	400	53	170	6	40	15	8.6	31.4	22	190	<200
Star Lake	0.5	12.8													

Sample Number	TiO_2%	FeOT%	Ag	Au	Ba	Co	Cr	Nb	Ni	Sc	Th	U	Y	Zn	Zr
Miguel Creek Dome	4										265				2960
Defiance	0.7	6.6									88				
Defiance	0.7	6.3									180				
Defiance	0.3	4.5									180				
Toadlena	0.4	11									530				
Sanostee	17.4	15.5									1150				24400
Sanostee	22.5	16.5								70	1240				26700
Sanostee	13.1	12.2									970				17040
Sanostee	9.6	8.7									710				10400
Standing Rock	4.3	24.4									700				2200
Standing Rock	2.2	22.4								20	600				1100
Standing Rock	6.3	34.4									180				3700

Sample Number	La	Ce	Sm	Eu	Tb	Yb	Lu	Reference
MCA101	81							Green et al. (1980)
MCA507	<20	<100						Green et al. (1980)
MCA508	810	1000						Green et al. (1980)
MCA509	<20	<100						Green et al. (1980)
2391	4250	8375	253	7		44	6	this report
2741	639	1267	58	8.3		17	4.3	this report
2740	655	1409	87	5.8		7.7	2.8	this report
2745	699	1410	67	6.7		9.9	3.1	this report
AA-8	814	1680	121	<4	16	34	7.6	Zech et al. (1994)
AA-9	1710	2740	161	8	18	82	14	Zech et al. (1994)
AA-10-1	32	60	55	<1	0.6	3	0.04	Zech et al. (1994)
AA-10-2	25	43	3.8	<1	0.6	<2	0.2	Zech et al. (1994)
AA-10-3	25	42	3.2	<1	<0.5	<2	0.2	Zech et al. (1994)
AA-10-4	150	280	18	<1	2.1	12	2	Zech et al. (1994)
AA-10-5	28	47	3.6	<1	0.6	<1	0.3	Zech et al. (1994)
AA-10-6	3100	586	36.8	<4	4.2	16	2.4	Zech et al. (1994)
AA-10-7	417	723	42.7	<5	4.7	25	4.1	Zech et al. (1994)
AA-10-8	355	595	31.5	<2	3.8	17	2.7	Zech et al. (1994)
AA-10-9	715	1170	76.2	6	9.2	50	10	Zech et al. (1994)
AA-10-10	572	1010	59.5	<6	7	225	6.7	Zech et al. (1994)
AA-10-11	160	280	16	4	1.6	8	1.4	Zech et al. (1994)
AA-10-12	1120	1840	128	<7	13	63	13	Zech et al. (1994)
AA-10-13	652	1100	60.8	<3	7.7	38	6.5	Zech et al. (1994)
AA-11	54	90	580	1	1.3	3	0.6	Zech et al. (1994)
AA-13	673	1140	68.7	4	7.9	36	5.9	Zech et al. (1994)
AA-14	452	947	47.7	3	6.6	23	3.8	Zech et al. (1994)
AA-16	1080	2080	105	5	16	66	12	Zech et al. (1994)
AA-17-1	40	61	4.3	<1	0.6	3	0.5	Zech et al. (1994)
AA-17-2	559	870	49.1	<4	6.2	36	6.1	Zech et al. (1994)
AA-17-3	342	570	34.3	<3	3.4	24	3.7	Zech et al. (1994)
AA-17-4	411	678	44.7	<5	5.9	20	3.7	Zech et al. (1994)
AA-17-5	298	523	32.5	<3	4.4	18	3	Zech et al. (1994)
AA-19	373	726	37.3	3	5.2	22	3.9	Zech et al. (1994)
AA-20	580	1210	69.1	5	10	42	7.3	Zech et al. (1994)
AA-21	772	1380	89.5	5	9.4	37	5.9	Zech et al. (1994)
AA-36-NW	559	949	63.5	<3	8.3	39	7	Zech et al. (1994)
AA-36-SE	381	645	36.4	3	5	25	4.5	Zech et al. (1994)
AA-37	577	1150	63.9	6	8.2	44	6.9	Zech et al. (1994)

Sample Number	La	Ce	Sm	Eu	Tb	Yb	Lu	Reference
FA-1	71	82	637	<1	1.3	2	0.5	Zech et al. (1994)
Star Lake								Dow and Batty (1961)
Miguel Creek Dome								Dow and Batty (1961)
Defiance								Dow and Batty (1961)
Defiance								Dow and Batty (1961)
Defiance								Dow and Batty (1961)
Toadlena								Dow and Batty (1961)
Sanostee								Dow and Batty (1961)
Sanostee								Dow and Batty (1961)
Sanostee								Dow and Batty (1961)
Sanostee								Dow and Batty (1961)
Standing Rock								Dow and Batty (1961)
Standing Rock								Dow and Batty (1961)
Standing Rock								Dow and Batty (1961)