Beach Placer Mineral Deposits along Localized Paleoshorelines of the Western Interior Seaway, Upper Cretaceous Fox Hills Sandstone, Eastern Denver Basin, Colorado

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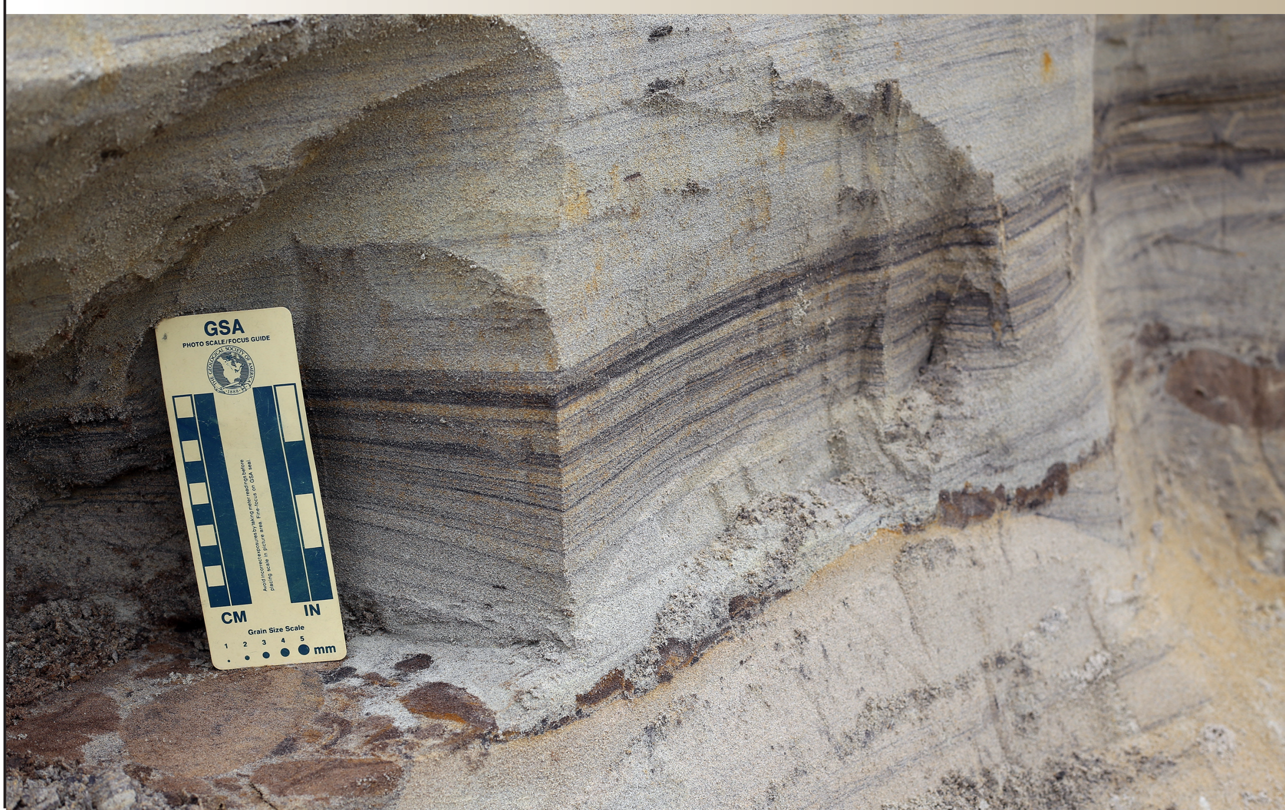

Resource Series 48

Colorado Geological Survey - 2020

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Cover: Heavy mineral laminae in beach placer deposits of the Fox Hills Sandstone, Limon area, Colorado.

DOI: https://doi.org/10.58783/cgs.rs48.kzgr9849

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ACKNOWLEDGMENTS

This project was funded by the Colorado Geological Survey (CGS). The CGS would like to thank the Colorado State Land Board and Joe Frasier at Solid Rock Red Angus, Frasier Farms River Bend Ranch, for property access. Analysis of select samples was conducted by the Peter Hooper GeoAnalytical Lab at Washington State University. Thanks to Jae Erickson at the thin section lab at the Colorado School of Mines (Mines) for producing thin sections of the very friable sandstone samples collected during this study. Automated mineralogy analysis and subsequent mineralogy mapping was performed at Mines. Thin section scans were performed at the U.S. Geological Survey facility in Denver. Additional information associated with historical coal exploration in this area was provided by Bob Kirkham. The late Bill Collins, who was involved with some of the past exploration activities in the study area, also provided background information about beach placers in the Fox Hills Sandstone at the property. Thanks to Larry Scott, Kassandra Lindsey, and others at the CGS who assisted with this report. The CGS would also like to thank Jim Cappa, Bob Raynolds, Julie Herrick, and Janet Slate for their reviews of this document. All photographs by Mike O'Keeffe unless otherwise noted.

DISCLAIMER

INTRODUCTION

Beach placers deposited within the Fox Hills Sandstone along the eastern flank of the Denver Basin contain heavy minerals typically associated with this deposit type (**Figure 1**). These marine beach placers, or paleoplacers, were deposited in the Late Cretaceous along the western edge of the retreating Western Interior Seaway (WIS). Preliminary investigations in the 1950s and 1960s, and expanded exploration in the 1990s, determined that these deposits contain potential critical mineral resources as recently defined by Fortier and others (2018) including titanium (ilmenite and rutile) and zirconium. Analysis of samples during these exploration activities also reported the presence of other critical minerals including hafnium associated with zircon and the rare earth element (REE)-bearing minerals allanite, monazite, and xenotime.

A limited investigation in this area during 2018 and 2019 was led by the Colorado Geological Survey (CGS) to provide additional information on the nature of these critical mineral deposits, including critical mineral concentrations of REEs, and the stratigraphy of an exposed paleoshoreline in the Fox Hills Sandstone. This effort may assist with future mineral exploration efforts and provide insight into the retreat of the WIS during the Late Cretaceous. Currently, there is a paucity of available information about these deposits and therefore, an additional goal of this study is to provide a summary of the history and exploration activities conducted in this area. The following tasks were completed during this investigation:

- Review of publicly available documents and publications;
- Collection of samples and stratigraphic analysis of accessible outcrops;
- Mineralogical analysis of select samples; and
- Laboratory analysis of samples from locations for REEs and other critical minerals.

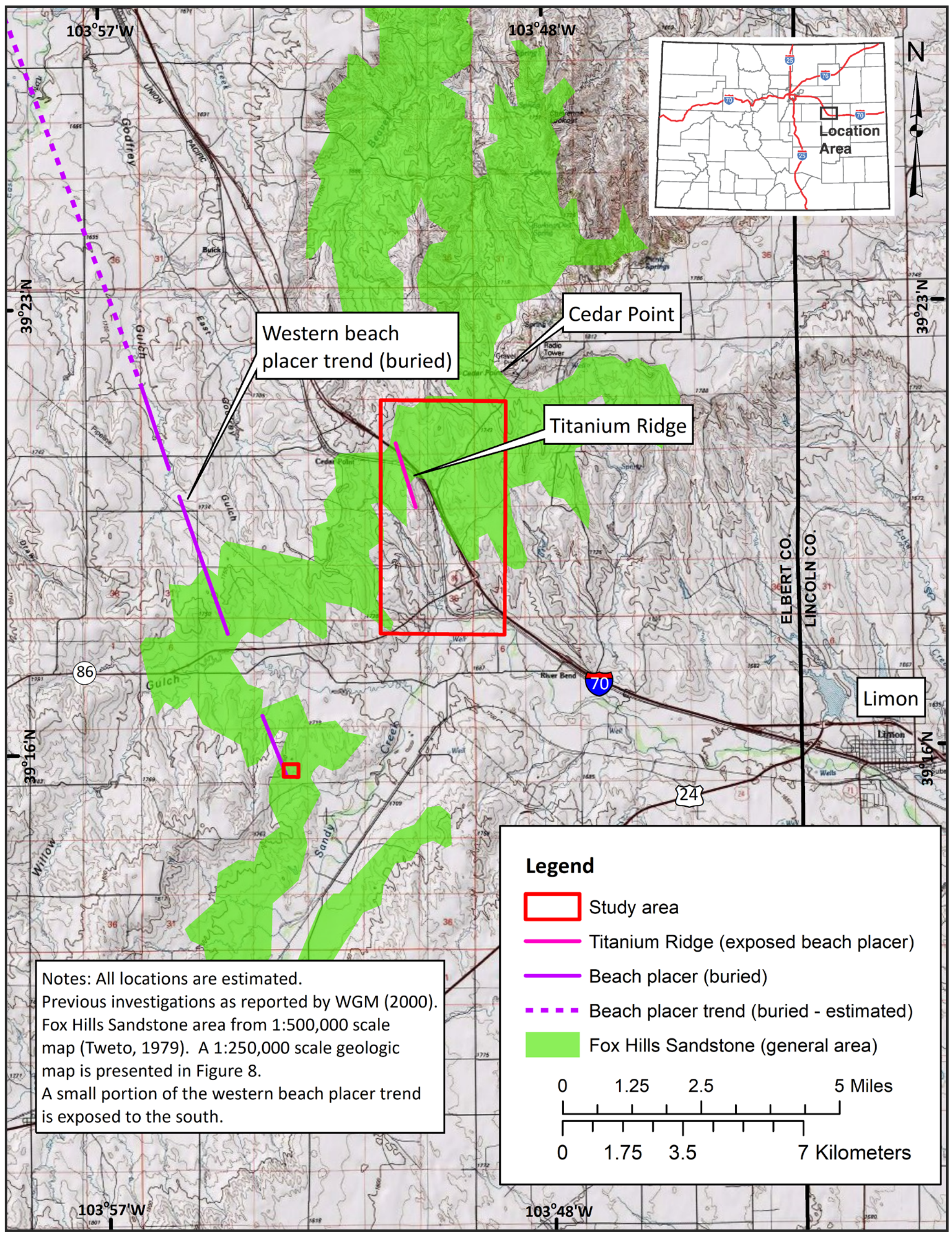


***Figure 1.** Study area location map, Limon area, Colorado.*

BEACH PLACER BACKGROUND

Beach placers form in marine coastal settings and, in many parts of the world including the United States (U.S.), contain economic deposits of heavy minerals. Heavy minerals associated with beach placers typically include titanium-bearing minerals (ilmenite, rutile, anatase, and the titanium-mineral alteration product leucoxene), zircon, garnet, and additional minerals (**Table 1**) that are sourced from metamorphic, igneous, or sedimentary rocks. A recent update to the U.S. critical mineral list (Fortier and others, 2018) included several commodities frequently associated with the minerals found in beach placers, including titanium, zirconium, hafnium, and REEs. As reported by Fortier and others (2018) and summarized here, critical minerals are generally defined as minerals that are essential to the economic and national security of the U.S. These minerals serve an essential function in the manufacturing of a product and their supply chains are often susceptible to disruptions largely due to geopolitical or economic reasons (Fortier and others, 2018).

In the western interior of the U.S., Cretaceous beach placer deposits occur in several states including Colorado, Wyoming, New Mexico, Montana, and Utah. In eastern Colorado, west of Limon, beach placers occur in outcrops of the Upper Cretaceous Fox Hills Sandstone and in the subsurface (Malan, 1965; WGM, 2000; Pirkle and others, 2012) (Figure 1). The deposits occur in the regressive marine sandstones of the WIS deposited across this area, where paleoshoreline positions of the final regression of the WIS in the U.S. are documented on the basis of stratigraphy and other studies (Gill and Cobban, 1973; Raynolds and Dechesne, 2007). These beach placers generally contain elevated concentrations of titanium and zircon and potentially other critical minerals. To better understand the deposits observed in the Fox Hills Sandstone, the following sections present background information associated with the depositional environments, economics of beach placers, and a summary of research conducted on some of the Cretaceous beach placers in other parts of Colorado and nearby states.

DEPOSITIONAL ENVIRONMENTS

Beach placers occur in modern and paleocoastal environments. Heavy minerals, generally defined as minerals with specific gravities greater than ~2.85 (Van Gosen and Ellefsen, 2018) (Table 1), are typically resistant to weathering and, after being discharged by rivers and estuaries to the sea, can be concentrated by natural coastal processes in areas along the coast and especially on and near the shoreline. Beach placers containing heavy minerals are deposited in several depositional environments including deltas, tidal deltas, tidal lagoons, dunes, beach faces, headlands, spits, barrier islands, and in channels and floodplains of rivers, streams, and estuarine channels (see Figure 1 in Hou and others, 2017; Stanaway, 2012; Van Gosen and Ellefsen, 2018). Depositional environments associated with coastal landforms are complex and various nomenclature is used by different authors for specific areas along the shore. As presented by other authors, marine depositional environments from the beach area to the sea include dunes, backbeach, foreshore, and shoreface environments (Houston and Murphy, 1977; Roehler, 1993; Clifton, 2006; Van Gosen and others, 2014a; Hou and others, 2017). **Figure 2** shows the general location of these depositional areas in cross section. Some of these specific environments that may pertain to the study area are summarized below.

Table1. *Typical heavy-minerals associated with beach placer deposits modified from Van Gosen and others (2014a).*

Specific Gravity	Heavy Mineral	General Composition
5.3	Hematite	Fe_2O_3
5.2	Magnetite	Fe_3O_4
5.0	Pyrite	FeS_2
4.8	Pyrolusite	MnO_2
4.6 – 5.4	Monazite	$(Ce,La,Y,Th)PO_4$
4.7	Ilmenite	$FeTiO_3$
4.7	Zircon	$(Zr,Hf,U)SiO_4$
4.4 – 5.1	Xenotime	YPO_4
4.4	Goethite	FeO(OH)
4.2 – 4.3	Rutile	TiO_2
4.0	Corundum	Al_2O_3
3.8 – 4.2	Leucoxene	$FeTiO_3$ to mostly TiO_2
3.7 – 3.8	Staurolite	$Fe_2Al_9O_6(SiO_4)_4(O,OH)_2$
3.6 – 4.0	Limonite	$FeO{\cdot}OH{\cdot}nH_2O$
3.5 – 4.1	Spinel	$MgAl_2O_4$
3.4 – 3.6	Sphene (titanite)	$CaTiO(SiO_4)$
3.4 – 3.5	Epidote	$Ca_2(Al, Fe)Al_2O(SiO_4)(Si_2O_7)(OH)$
3.1 – 4.3	Garnet	$(Fe, Ca, Mg, Mn)\ Al_2Si_3O_{12}$
3.6 – 3.7	Kyanite	Al_2SiO_5
3.2	Sillimanite	Al_2SiO_5
3.2	Andalusite	Al_2SiO_5
3.0 – 3.3	Tourmaline	$(Na,Ca)(Li,Mg,Al)(Al,Fe,Mn)_6(BO_3)_3(Si_6O_{18})(OH)_4$

- **Strandline, shoreline, or coastline** – the level at which a standing body of water meets the land where the strandline is the beach area that lies just above the sea or ocean (Van Gosen and others, 2014a).

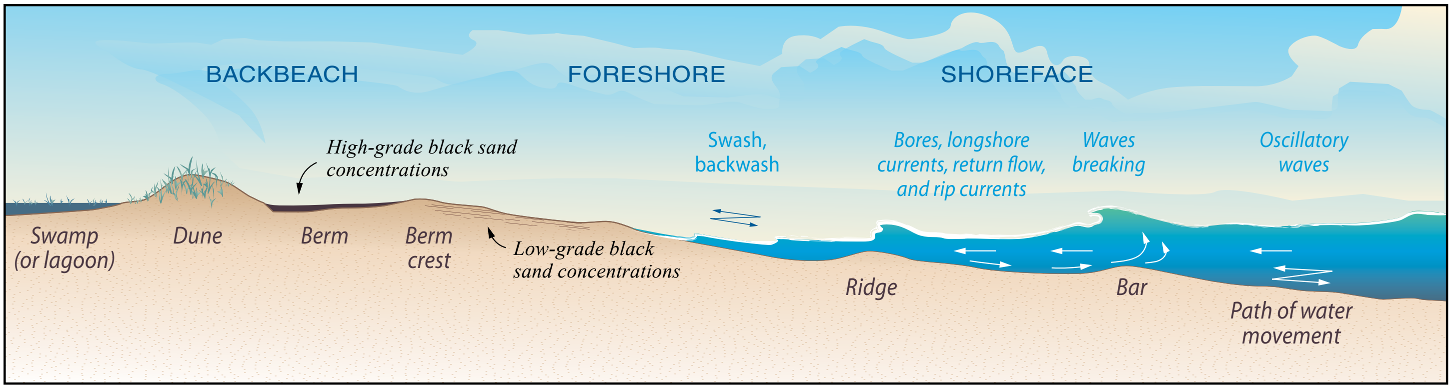


Figure 2. *Schematic diagram showing shoreline depositional environments. Modified from Houston and Murphy, 1977.*

- **Shoreface** –located between the fair-weather wave base to the low tide level and is subdivided into the lower, middle, and upper shoreface. It has a relatively steep slope and extends from the foreshore to the flatter shelf or basin platform (Clifton, 2006).

- **Foreshore** –beach that is covered and uncovered by the sea from high tide to low tide and sometimes referred to as the beach face. This area includes the *"swash"* zone—the area where waves constantly lap against the upper foreshore and/or lower foreshore during seasonal low tides (Houston and Murphy, 1977). The upper foreshore usually has a slightly steeper slope than the lower foreshore (Houston and Murphy, 1977) and low energy waves deposit heavy minerals on the upper foreshore in thin laminae. As reported by Houston and Murphy (1977), moderate-intensity waves can carry heavy minerals over the berm crest resulting in draping of the heavy-mineral laminae over the berm where the heavy-mineral laminae dip away from the shore on one side and towards the shore on the other. These berms can be eroded and sediment can be redeposited in different areas along the berm crest resulting in heavy-mineral laminae deposited at slightly different angles (Houston and Murphy, 1977).

- **Backbeach or Backshore** –an area between the crest of the berm, that forms at the upper limit of fair weather wave action at high tide, and extends shoreward to the dunes (Van Gosen and others, 2014a). Houston and Murphy (1962) indicate that higher-grade (higher concentration of heavy minerals) beach placers within Cretaceous sandstones occur in the backbeach. Higher-intensity waves generated during major storms transport sediment over the berm crest to the backbeach as observed in modern backbeach deposits along the Mississippi Gulf Coast. Other beach placer deposits along the upper forebeach may be eroded and redeposited in the backbeach during storm events (Houston and Murphy, 1977). Storm waves sometimes carry sediment over the backbeach and coastal dunes (Hesp, 1999) resulting in deposits, known as washover facies or deposits, beyond these areas (Schwartz, 1982; Clifton, 2006; Shaw and others, 2015). Washover deposits and dunes have been identified in the Fox Hills Sandstone in Wyoming (Roehler, 1993) and occur on modern coasts as shown in **Figure 3**.

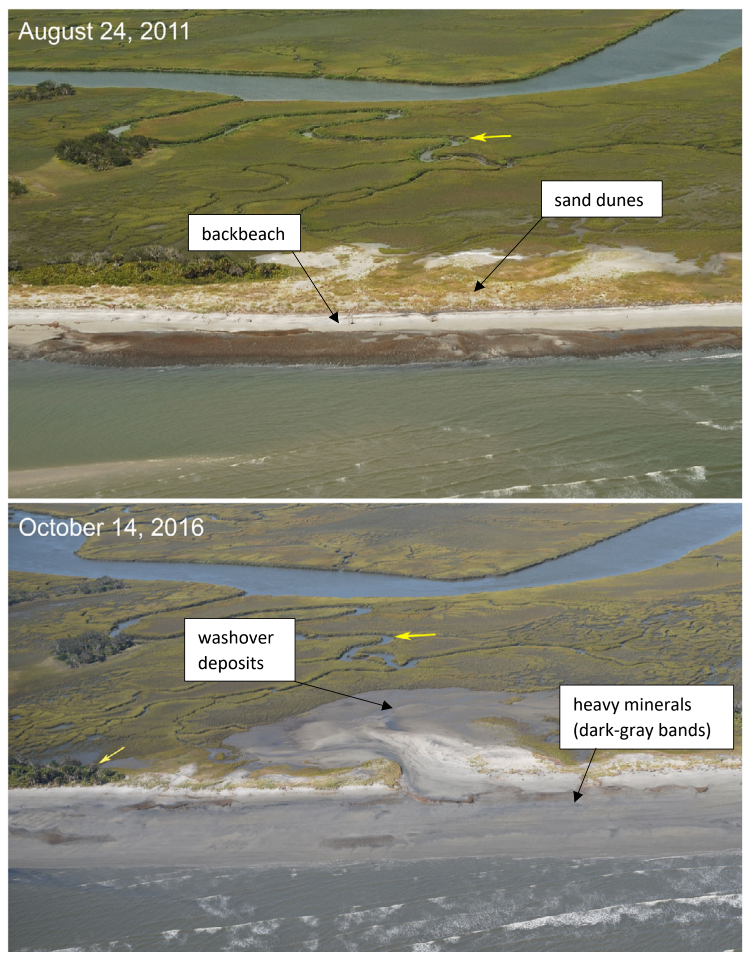


Figure 3. *Photos of modern washover deposits along the Georgia coast. Deposits along St. Catherines Island before (top) and after (bottom) Hurricane Matthew in 2016 (USGS, 2020 - public domain).*

- **<u>Dunes</u>** –coastal dunes typically form nearer to the shore relative to the backbeach environment (Houston and Murphy, 1977). After deposition in the backbeach, heavy minerals may be transported and concentrated on coastal dunes by the wind (Hou and others, 2017).

Generally, based on modern studies of beach sand deposits along the Mississippi Gulf Coast, *"heavy minerals are deposited primarily by wind-generated waves that result from squalls or storms at sea. The heavy minerals may be deposited on different parts of the beach depending on the wave height and tide"* (Houston and Murphy, 1977, page A10). Heavy-mineral laminae, similar to those visible in outcrops of the Fox Hills Sandstone of this investigation, were observed during investigations of backbeach and washover deposits along the New York coastline after Hurricane Sandy in 2012 (La Selle and others, 2017).

Most of the Upper Cretaceous beach placer sandstones studied by Houston and Murphy (1970) in the western U.S. reportedly formed either at the top of the foreshore or at the base of dunes (i.e. backbeach) where higher-grade black sand concentrations were deposited by storm waves. Houston and Murphy (1977) report that backbeach placer deposits were more likely to be preserved compared to foreshore deposits as the latter are continuously eroded by wave action. For more information about coastal processes and other factors associated with the formation of beach placers see Van Gosen and others (2014a) and Hou and others (2017, especially Section 3.0).

BEACH PLACER MORPHOLOGY

Beach placers typically lie along paleoshoreline strike, are stacked stratigraphically, and represent changing sea levels over time (Van Gosen and others, 2014a). For example, in the southeastern U.S., marine beach placers occur with other beach deposits that are typically aligned along paleoshorelines as shown in **Figure 4**. As reported by Van Gosen and others (2014a), higher concentrations of heavy mineral-rich sediment are typically lens shaped, can be tens of meters thick, occur along the length of the strandlines, can be offset stratigraphically, and typically are separated by lower heavy-mineral content intervals.

Because they are associated with coastlines, beach placers can extend for several kilometers (km) (e.g., 10 km or ~6 miles) with each individual body of heavy minerals typically ~1 km (~0.6 miles) wide and more than 5 km (~3 miles) long (Van Gosen and others, 2014a). The economic portions of the beach placers are usually not as thick and generally range between 3 and 45 meters (m) (~10 and 150 feet [ft]) (Van Gosen and others, 2014a). Examples of the horizontal ex-

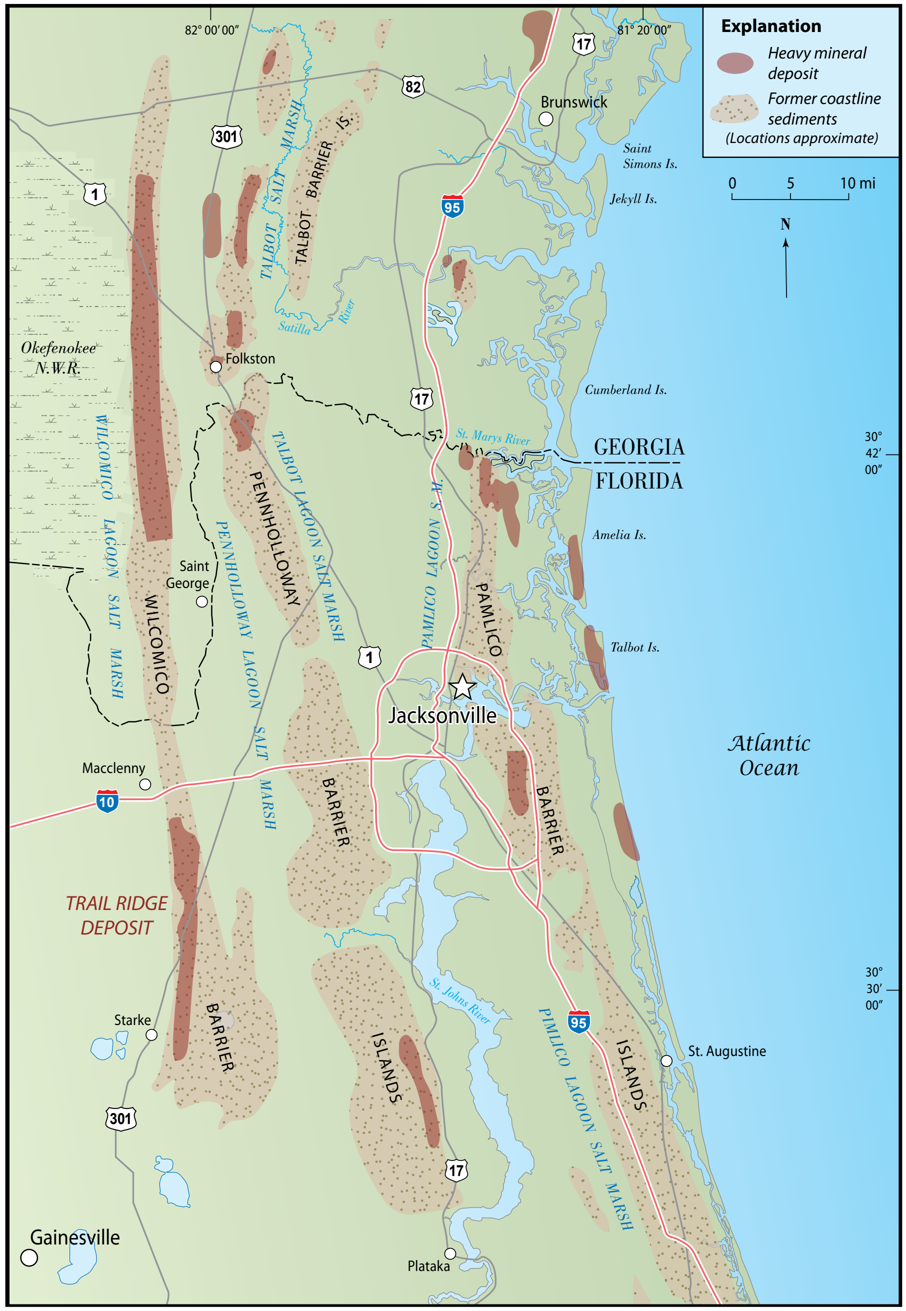


Figure 4. Map showing select heavy-mineral beach placers in the southeastern U.S. Note the elongated and discontinuous nature of these beach placers that were deposited along paleo-coastlines. Modified from Hoyt, 1969; Pirkle and others, 2013.

tent of beach placers are provided by Van Gosen and others (2014a) and summarized below.

- The Jacinth deposit in the Eucla Basin, South Australia is ~900 m (0.6 miles) wide by 5 km (~3 miles) long.
- The longest deposit in the Murray Basin, New South Wales, Australia, is ~14.5 km (9 miles) long and contains individual deposits up to 130 m (~430 ft) wide.
- The Atlas deposit in the northern portion of the Perth Basin, Western Australia, is ~7 km (~4 miles) long and up to 400 m (~1,300 ft) wide.
- In north-central Florida, the Trail Ridge deposit is an eolian dune complex containing heavy mineral deposits along a trend for at least 29 km (18 miles) with an average width of ~2 km (1 mile).

WESTERN U.S. UPPER CRETACEOUS BEACH PLACERS

A map showing the location of some of the Upper Cretaceous beach placers identified in Colorado, Wyoming, and New Mexico is included as **Figure 5**. Upper Cretaceous beach placers are also located in U.S. states, Montana, Arizona, and Utah, and Canada and Mexico. Beach placers in Colorado were identified in the Upper Cretaceous Point Lookout Sandstone, Pictured Cliffs Sandstone, and intertongues within the Menefee Formation southwest of Durango. This group of beach placers is sometimes referred to informally as the Shiprock group (Dow and Batty, 1961). Other beach placers are reported in the Mesaverde Group east of Grand Junction at Grand Mesa, and near the Wyoming border south of Rock Springs, Wyoming (Murphy and Houston, 1955; Murphy, 1956; Chenoweth, 1957; Dow and Batty, 1961; Houston and Murphy, 1962; Houston and Murphy, 1970; Houston and Murphy, 1977). Beach placers in the Point Lookout Sandstone contain titanium minerals, magnetite, zircon, and monazite. Similar deposits and mineral assemblages occur to the south in New Mexico (Dow and Batty, 1961).

Heavy minerals in the Upper Cretaceous Rock Springs Formation in Wyoming are composed dominantly (~85%) of titanium-bearing minerals (e.g., ilmenite, rutile) as well as zircon and lesser amounts of tourmaline, rutile, garnet, sphene, hornblende, apatite, and other heavy minerals (Roehler, 1989). Monazite is a common constituent of the black sandstones in Wyoming and is recognized in most of the deposits in Colorado, Montana, New Mexico, and Arizona. Reportedly, unlike other minerals in the beach placers, the distribution of monazite is variable and occurs in larger amounts in some samples (~3 or 4% of the heavy mineral fraction) but is absent in other samples from the same deposit. Monazite grains also tend to be concentrated in the finer grained sediment fraction (Houston and Murphy, 1962).

As reported by Houston and Murphy (1977), the Cretaceous sandstones they studied in the western U.S. contain beach placers typically underlain by nearshore marine sandstone and overlain by nonmarine fine-grained sandstone, carbonaceous shale, and coal. Heavy minerals are typically observed in laminated sandstone with alternating black and white banding. These bands average ~15% heavy minerals at the base with an overlying massive *"black"* (i.e. heavy mineral rich) sandstone composed of layers with up to 90% heavy minerals at the top (Houston and Murphy, 1977). The alternating light- and dark-colored laminae are a result of reworking and separation of sediment by waves in the swash zone. Thick (e.g., up to 0.3 m [1 ft] as shown in Houston and Murphy, 1977—see Figure 11 from their publication) heavy-mineral-rich layers observed in the uppermost foreshore or backbeach are thought to be produced by storms (Houston and Murphy, 1977).

Houston and Murphy (1977) indicate that portions of the Cretaceous beach placers of Colorado, Montana, Wyoming, Utah, and Arizona may be associated with storm deposits.

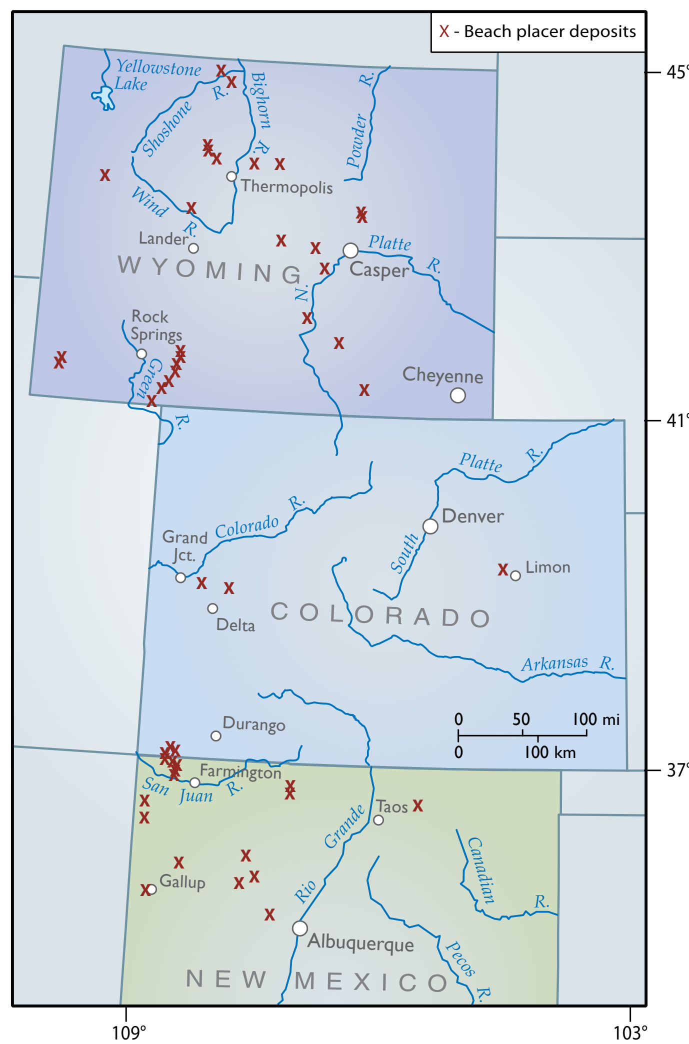


Figure 5. *Select beach placer locations in the western U.S. (after Houston and Murphy, 1977).*

Higher-intensity waves and tides can carry heavy minerals to the backbeach while depositing lighter sediments seaward. During storm events, heavy-mineral deposits on the forebeach and berm crest are partially disaggregated and redeposited on the backbeach, increasing the concentration of heavy minerals in the backbeach (Houston and Murphy, 1977). Preservation of the beach placers is dependent upon the deposition of overlying sediments that provide protection from erosion by the advancing sea (Houston and Murphy, 1977). Houston and Murphy (1977, page A21) also report that the uppermost black sandstone of the backbeach, containing much of the heavy-mineral content in some of the beach placers, may be the *"most reliable shoreline marker known in rocks of Cretaceous age."* These shorelines are likely only local features; however, regional stratigraphic studies in some areas indicated that their strikes correlate with each other regionally (Houston and Murphy, 1977). The shape, width, and thickness distribution of beach placers may provide information associated with storm wind directions, morphology of beaches, and approximate measures of paleotidal ranges (Houston and Murphy, 1977).

Summary of Previously Reported Sediment Source Areas

The following paragraph is summarized from Houston and Murphy (1977). Some sedimentary rocks of the Upper Cretaceous in Montana and northern Wyoming contain beach placers with major episodes of deposition between ~82 and 80 million years ago (Ma) and ~72 and 71 Ma in the northern areas (e.g., Montana). These two time periods are speculatively linked to igneous activity and/or deformation associated with the emplacement of the Idaho and Boulder batholiths (Houston and Murphy, 1977). Such igneous events are potential sources of heavy minerals and clastic material that were transported to the shores of the WIS east of the rising Cordilleran orogenic belt.

Historically, the primary source areas associated with beach placer heavy minerals include high-grade metamorphic and igneous rocks. Based on dating of detrital zircon, Houston and Murphy (1962) suggest a source area in the Precambrian rocks to the west, perhaps from the Sevier orogenic belt (although this is not specified by the authors) and, the Idaho batholith located in central Idaho and western Montana. Roehler (1989) reported that the beach placers in the McCourt Sandstone Tongue of the Rock Springs Formation in Wyoming were likely sourced from the Sevier orogenic belt located ~240–400 km (~150–250 miles) to the west of these deposits. Sediment deposited into the WIS was carried by longshore currents to the southwest, parallel to the shoreline, and rapid coastal subsidence and burial preserved these deposits (Roehler, 1989).

BEACH PLACER COMMODITIES AND ECONOMICS

Beach placer deposits are currently the principal source of global titanium and zirconium supplies (Hou and others, 2017). Since 2010, mining of coastal beach placers has accounted for 96% of zircon, 90% of rutile, 30% of ilmenite, and 80% of monazite produced by the global mineral industry (Van Gosen and Ellefsen, 2018). These deposits occur globally and are mined in several countries including Australia, India, South Africa, and the southeastern U.S. Van Gosen and others (2014a) provide a description of these deposits. In 2018, ilmenite and rutile concentrates were primarily produced in the U.S. from beach placers located in Georgia and Florida where zircon was also mined as a coproduct.

In 2018, ~90% of the titanium mineral concentrate produced in the U.S. was used for pigments while the rest was used in welding-rod coatings and for manufacturing carbides, chemicals, and metal (U.S. Geological Survey [USGS], 2019). The leading uses for zircon in 2018 were for ceramics, foundry sand, opacifiers, and refractories. Zirconium metal, used in the chemical process and nuclear energy industries, and hafnium metal, used in superalloys, are also both produced from zircon. Zircon typically contains zirconium and hafnium at a ratio of ~36 to 1. Other uses of zircon include abrasives, chemicals, metal alloys, and welding-rod coatings (USGS, 2015; USGS, 2019).

Other heavy minerals sometimes recovered during beach placer mining include garnet and the REE-bearing minerals monazite and xenotime (Van Gosen and others, 2014a, 2014b; Hou and others, 2017). REEs are generally subdivided into two groups: the light REEs (LREE) and heavy REEs (HREE). The LREEs include lanthanum through gadolinium or atomic numbers 57 through 64. Promethium is usually not included in the LREEs because it only exists in very small concentrations naturally. The HREEs include terbium through lutetium, atomic numbers 65 through 71, and yttrium, atomic number 39. Yttrium is included because it has similar chemical and physical properties to the HREEs (Van Gosen and others, 2014b; Van Gosen and others, 2017). The definitions of LREE and HREE provided above are used within this report. Studies sometimes include gadolinium in the LREEs (Long and others, 2010) while others group europium and gadolinium with the HREEs (Van Gosen and others, 2014b).

In 2018, garnet was primarily used as an abrasive, in water-filtration media, and for cutting applications (USGS, 2019). REEs occur primarily in monazite but xenotime is also sometimes present. Monazite has been recovered from beach placers in Australia, China, India, and several other countries including the U.S. (Van Gosen and others, 2014a, 2014b). Although some REEs are mined in the U.S. from other deposit types, REE compounds and metals are largely imported.

Other trace minerals that occur in beach placers (Table 1) include cassiterite, corundum, kyanite, and tourmaline, but none of these minerals are typically recovered during mining (Van Gosen and others, 2014a). In 2018, REEs were primarily used as catalysts, in ceramics and glass, in metallurgical applications and alloys, and as polishing abrasives (USGS, 2019). Recent applications for REEs include magnets, batteries, steel production, and phosphors.

Heavy mineral ore grade in beach placers typically refers to average heavy mineral content in weight (wt.) %. Typical heavy mineral economic grades in these deposits are >2% and can exceed 10% (Van Gosen and others, 2014a). Heavy mineral grades can also be expressed in the percent of valuable heavy minerals, a term that typically includes minerals such as rutile, ilmenite, leucoxene (altered ilmenite with higher concentrations of titanium), and zircon depending on the deposit (Van Gosen and others, 2014a). Areas containing beach placers may reach hundreds of square kilometers. Individual deposits typically contain greater than 9 million metric tons (10 million short tons), with >2% heavy minerals, and are mined by open-pit methods (Van Gosen and others, 2014a). Combined resources within some areas, with the combined resources typically representing a group of beach placers, have been estimated to exceed 1,000 million metric tons with an average heavy mineral content exceeding 5% (Van Gosen and others, 2014a). Pirkle and others (2013) also provide some general guidelines for commercial beach placer deposit economics.

Many economic beach placer deposits are found in unconsolidated sand or very friable sandstone which makes the deposits easier to mine without blasting. In 2019, three mining operations in Florida and Georgia produced about 100,000 metric tons of TiO_2 (ilmenite and rutile), with zircon produced as a coproduct, from beach placer surface mining operations (USGS, 2019). Less economic deposits, sometimes referred to as *"noneconomic"* by others, occur in older (e.g., Cretaceous) consolidated sandstones (Hou and others, 2017). Beach placer deposits of the Cretaceous in the Rocky Mountain region of the U.S. are typically indurated which would increase their mining costs (Van Gosen and others, 2014a). As reported by Van Gosen and others (2014a, page 29), *"Presently, there are no active operations that recover heavy minerals from well-lithified sandstone."* Minor production of heavy mineral sands has occurred in the past from less-lithified sandstones (Hou and others, 2017).

GEOLOGY

A discussion of the regional geological setting and stratigraphy is presented in the following sections. Information from other authors on the geology and depositional environment of the Fox Hills Sandstone in eastern Colorado is also presented below.

REGIONAL GEOLOGIC SETTING

The study area is located ~100 km (65 miles) southeast of Denver and 14 km (9 miles) northwest of Limon, Colorado (Figure 1). The area lies on the eastern flank of the greater Denver Basin (a.k.a. Denver-Julesburg Basin or Denver-Cheyenne Basin), an asymmetrical structural depression that formed during the Laramide uplift of the Front Range from the Late Cretaceous to the middle Eocene (Tweto, 1975; Weimer, 1996; Dechesne and others, 2011) **(Figure 6)**. In this publication, the Denver Basin refers to the southern portion of the greater Denver Basin. The eastern Denver Basin is discussed in several other publications including Dane and Pierce (1936), Weimer (1973), Soister (1978a and 1978b), Sharps (1980), Kirkham and Ladwig (1979), Robson (1983), Raynolds (2002), Raynolds and Dechesne (2007), Raynolds and others (2007), and Dechesne and others (2011).

A generalized stratigraphic section and geologic map of the area are included as **Figures 7 and 8**, respectively. The geology in this area includes, from oldest to youngest: the Pierre Shale, Fox Hills Sandstone, Laramie Formation, Ogallala Formation, and overlying Quaternary eolian and alluvial deposits. Cretaceous rocks in the area gently dip ~1 degree or less to the west-northwest (Pirkle and others, 2012; WGM, 2000) towards the Denver Basin and strike north-northeast (Rocky Mountain Energy [RME], 1975). Surface expressions of faulting in the area are difficult to observe because of Quaternary deposit cover and the absence of outcrops. The trend of a single fault (the type of fault is not reported), identified during subsurface drilling in the area, is estimated to be north-northeast to south-southwest. Offset along this fault is estimated to be ~24 m (80 ft) to the southeast (RME, 1975).

The Pierre Shale, Fox Hills Sandstone, and Laramie Formation represent a series of Upper Cretaceous sediments that record the eastward regression of the WIS across what later formed as the Denver Basin. As the seaway retreated, at any given location, the relatively deeper marine deposi-

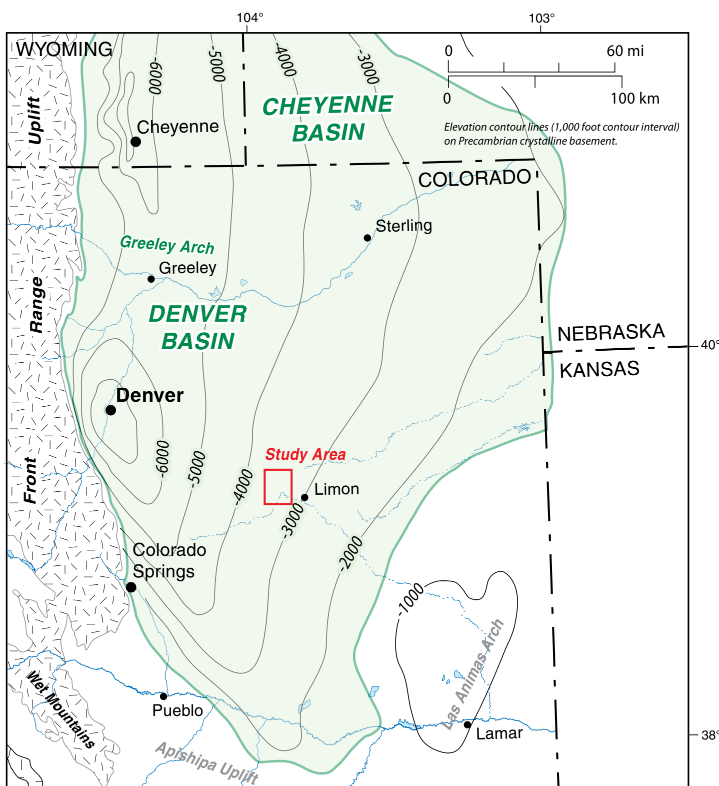


Figure 6. *Map showing the study area location in the Denver Basin near Limon, Colorado (after Dechesne and others, 2011).*

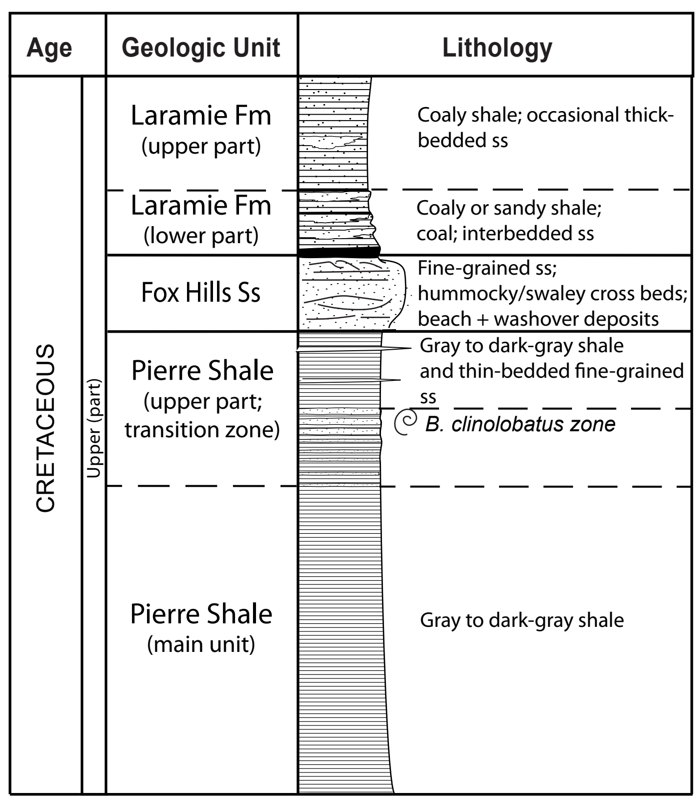


Figure 7. *General Upper Cretaceous stratigraphic column of the Titanium Ridge area, Colorado. Fm = formation. Ss = sandstone.*

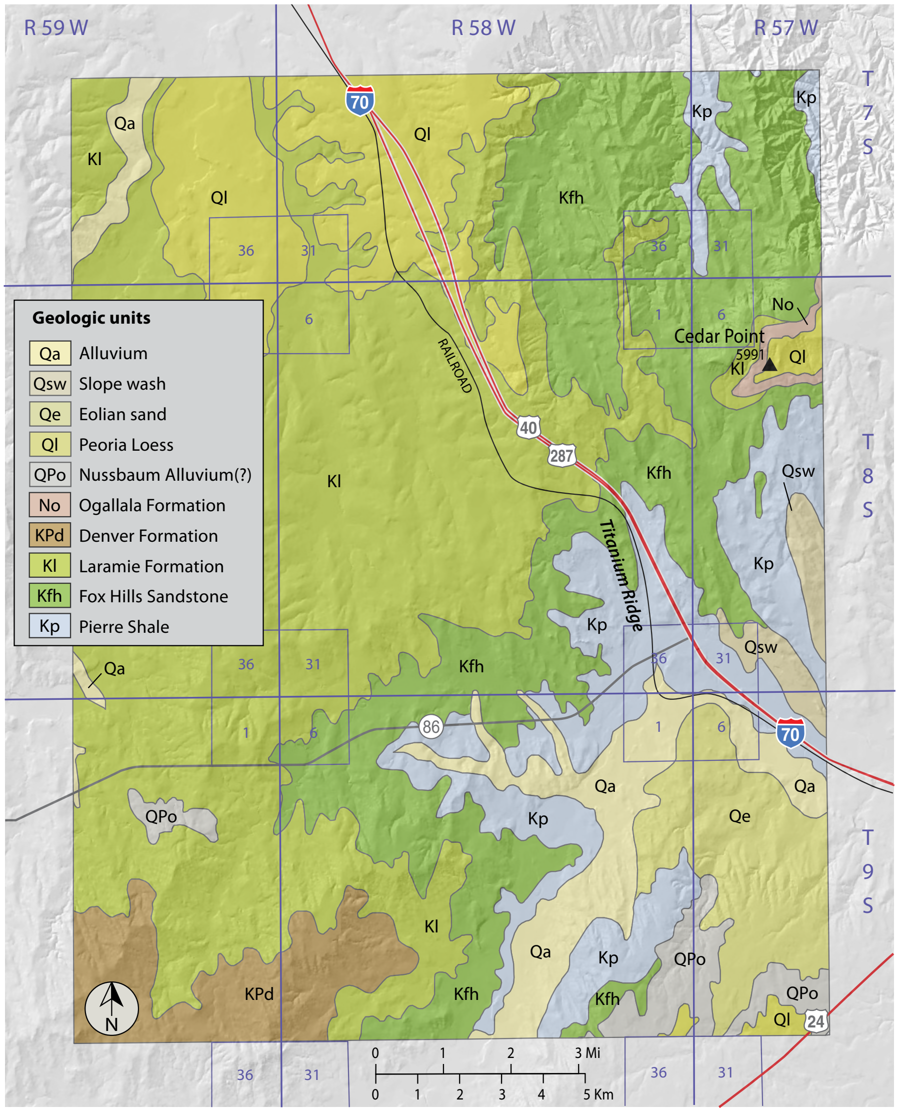


Figure 8. *Geologic map of the Titanium Ridge area, Colorado (1:250,000 scale after, Sharps, 1980).*

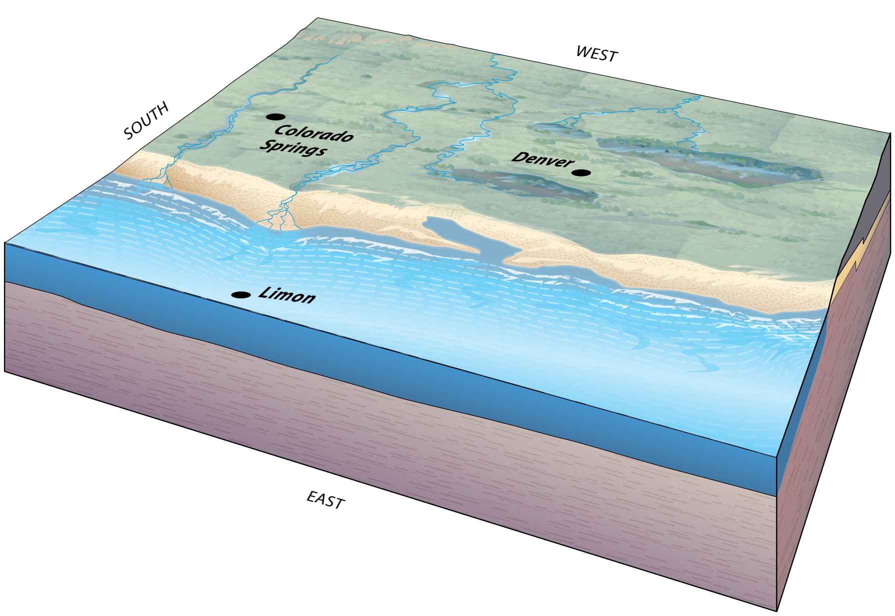


Figure 9. *General facies model and depositional setting of the Fox Hills Sandstone during the Late Cretaceous, Denver Basin, Colorado (from Dechesne and others, 2011). Pierre Shale (marine – blue), Fox Hills Sandstone (beach – yellow), and the Laramie Formation (coastal plain – green).*

tional setting (Pierre Shale) transitioned to an upper shoreface/beach environment (Fox Hills Sandstone), and finally to a terrestrial/coastal plain (Laramie Formation) depositional environment (Lee, 1915; Lovering and others, 1932; Lavington, 1933; Dane and Pierce, 1936; Cobban and Reeside, 1952; Weimer, 1960; Kirkham and Ladwig, 1980; Raynolds, 2002; Dechesne and others, 2011). **Figure 9** is a general facies model of the Fox Hills Sandstone relative to the Pierre Shale and Laramie Formation (Dechesne and others, 2011). The deposition of these formations is related to the overall regression of the WIS which deposited several stacked shoreface sequences **(Figure 10)**. These are discussed in more detail in the following sections. The relative position of the study area during the regression of the Cretaceous seaway is shown in **Figure 11** (Blakey, 2019).

The Pierre Shale underlies the Fox Hills Sandstone and crops out in the eastern portion of the study area. Generally, the upper ~120 m (400 ft) of the Pierre Shale consists of silty and sandy shale with interbedded thin-bedded sandstone (Sharps, 1980). The Fox Hills Sandstone is generally between ~60 and 75 m (200 and 250 ft) thick and consists of friable, fine- to medium-grained, massive, white or, less commonly, yellowish quartz-rich sandstone (Sharps, 1980). **Figure 12** shows the mapped extent of the Fox Hills Sandstone east of the Front Range; it includes a portion of the Laramie Formation grouped with the Fox Hills Sandstone by Tweto (1979). The contact between the Pierre Shale and the overlying Fox Hills Sandstone is transitional where marine sediments transition to shallower nearshore and shoreface sandstones (Raynolds, 2002). Photographs of various Fox Hills Sandstone outcrops in the study area are shown in **Figure 13a and 13b.**

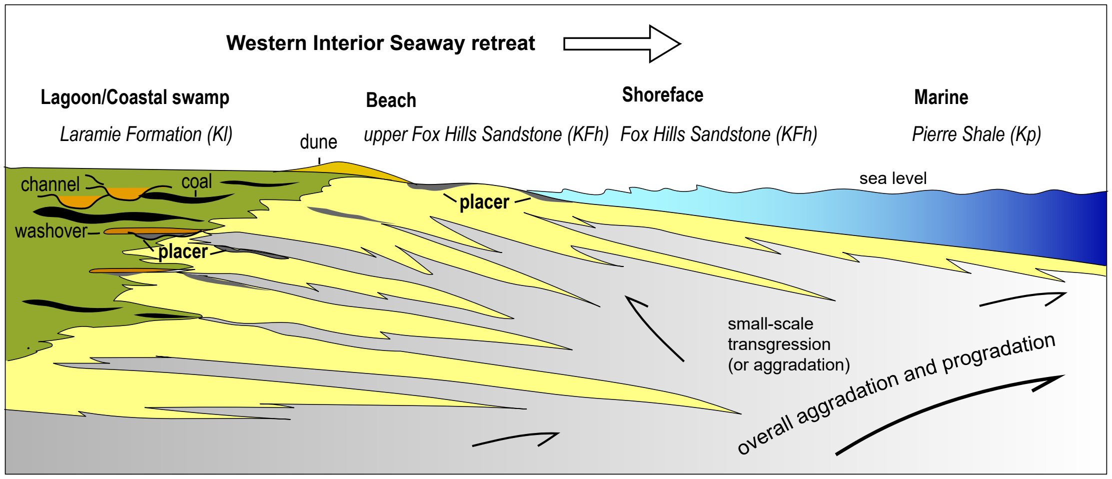


__Figure 10.__ General model of stacked shoreface sequences in the eastern Denver Basin, Colorado (modified from Raynolds and Dechesne, 2007).

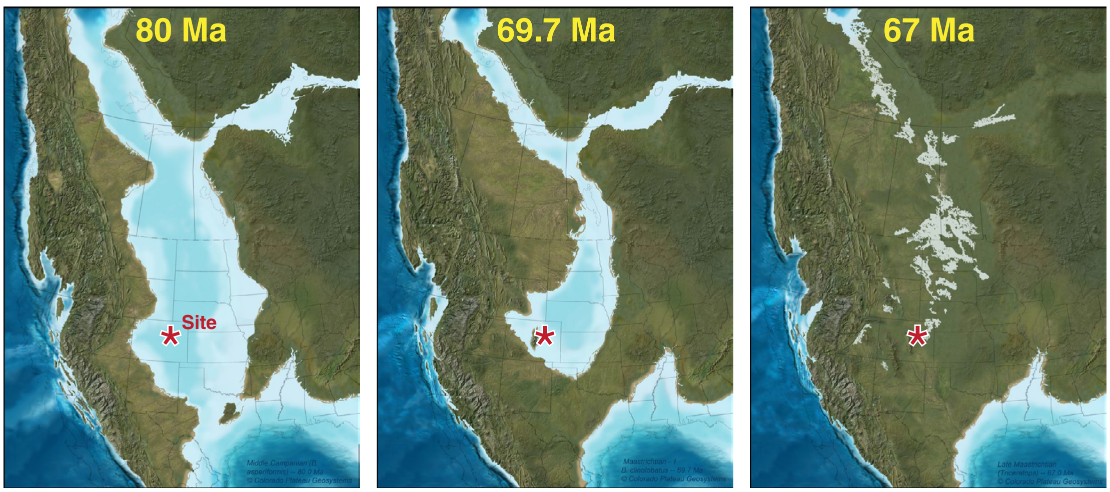
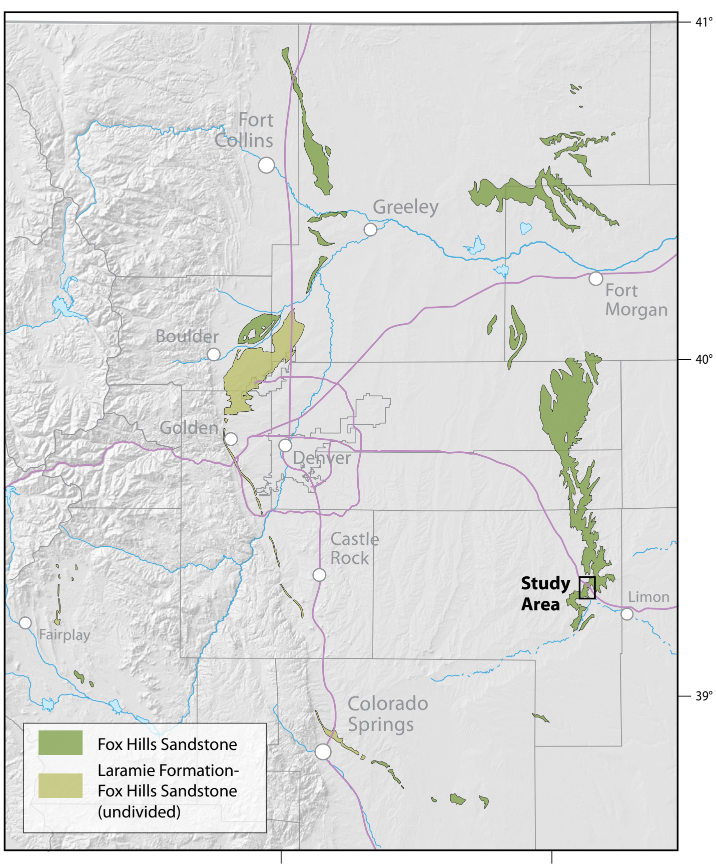


__Figure 11.__ Relative position of the Western Interior Seaway to the study area during the Late Cretaceous (Blakey, 2019).



The boundary between the Laramie Formation and underlying Fox Hills Sandstone can be defined in Colorado as the horizon between fine-grained predominantly fresh/brackish water deposits, with coals and lignitic shales, above, and predominantly marine deposits (e.g., sandstone) below (Lovering and others, 1932). However, this boundary can be difficult to pinpoint in the subsurface (especially south of the study area near Colorado Springs) due to estuarine and fluvial sandstones that occur near the base of the Laramie Formation and overlie the marine Fox Hills Sandstone (Raynolds, 2002; Dechesne and others, 2011). In the study area, subsurface resistivity geophysical logs have an increasing resistivity trace upwards to the top of the Fox Hills Sandstone, and this trend represents an increase in grain size (**Figure 14**). At the contact with the Laramie Formation, a sharp decrease in resistivity is due to the presence of finer grained shales. Occasional coalbeds give a typical high-resistivity spike on well logs (Dechesne and others, 2011).

__Figure 12.__ Mapped extents of the Fox Hills Sandstone and undivided Laramie Formation/Fox Hills Sandstone in northeastern Colorado (after Tweto, 1979, 1:500,000 scale).

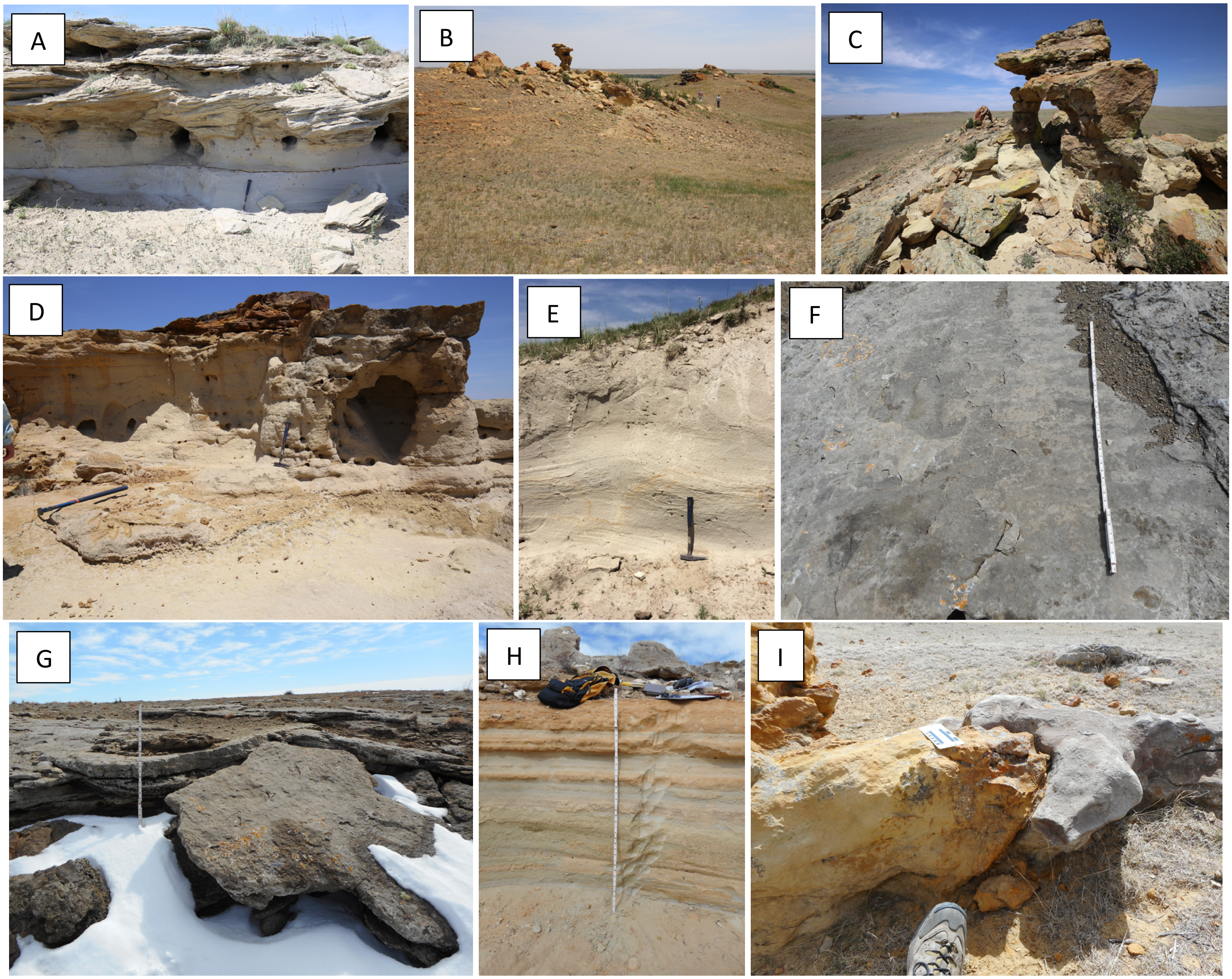


Figure 13a. *Photos of Fox Hills Sandstone in the study area near Limon, Colorado. Hammer is ~41 cm (16 inches) long, scale card is ~16.5 cm (6.5 inches) long, scale in G is ~0.8 m (2.5 ft) long, and the scale in F and H is ~1.2 m (4 ft). (A) ~90 m (300 ft) northeast of TR-02/ TR-03, heavy-mineral laminae were observed near the base of this sandstone outcrop; (B) Fox Hills Sandstone ridge near TR-12; (C) Arch in the Fox Hills Sandstone just west of TR-12; (D) Fox Hills Sandstone west of TR-12; (E) Fox Hills Sandstone at TR-01; (F) Wave ripples in the upper indurated part of the Fox Hills Sandstone at TR-07 (S. Keller); (G) Sigmoidal crossbedding in the upper indurated Fox Hills Sandstone at TR-07 (S. Keller); (H) Fox Hills Sandstone at TR-10 with heavy-mineral laminae (S. Keller); (I) Fox Hills Sandstone at TR-11 (S. Keller), scour area where oxidized orange and white sandstone channel fill occurs within the gray sandstone.*

The overlying Laramie Formation can be greater than ~80 m (270 ft) thick and consists of silty clay and claystone, sandy claystone, sandstone, and coal (Tetra Tech, 2007). The lower portion of the formation is predominantly shale, claystone, coal, and lenticular channel sandstone deposited in a delta plain environment (Kirkham and Ladwig, 1980). Within the study area, coal in the Laramie Formation consists of two main beds: an *"A"* coal bed and underlying *"B"* coal bed with two additional thinner coal beds referred to as the *"A-upper"* and *"B-upper"* coals. Based on drilling data, the A and underlying B coal beds range in thickness from ~0.2 to 4 m (0.6 to 14 ft) while the A- and B-upper coals range in thickness from 0.2 to 2.6 m (~0.5 to 8.5 ft) and 0.2 to 0.8 m (~0.7 to 2.5 ft), respectively (Tetra Tech, 2007).

FOX HILLS SANDSTONE STRATIGRAPHY - EASTERN DENVER BASIN

The upper portion of the Upper Cretaceous Fox Hills Sandstone is dominantly fine- to medium-grained sandstone deposited in deltaic and barrier island shallow marine environments during the recession of the WIS (Weimer, 1973; Weimer and Tillman, 1980; Kirkham and Ladwig, 1980). In the Denver Basin, the Fox Hills Sandstone is described as a *"series of aggradational sandstone bodies that accumulated during the episodic*

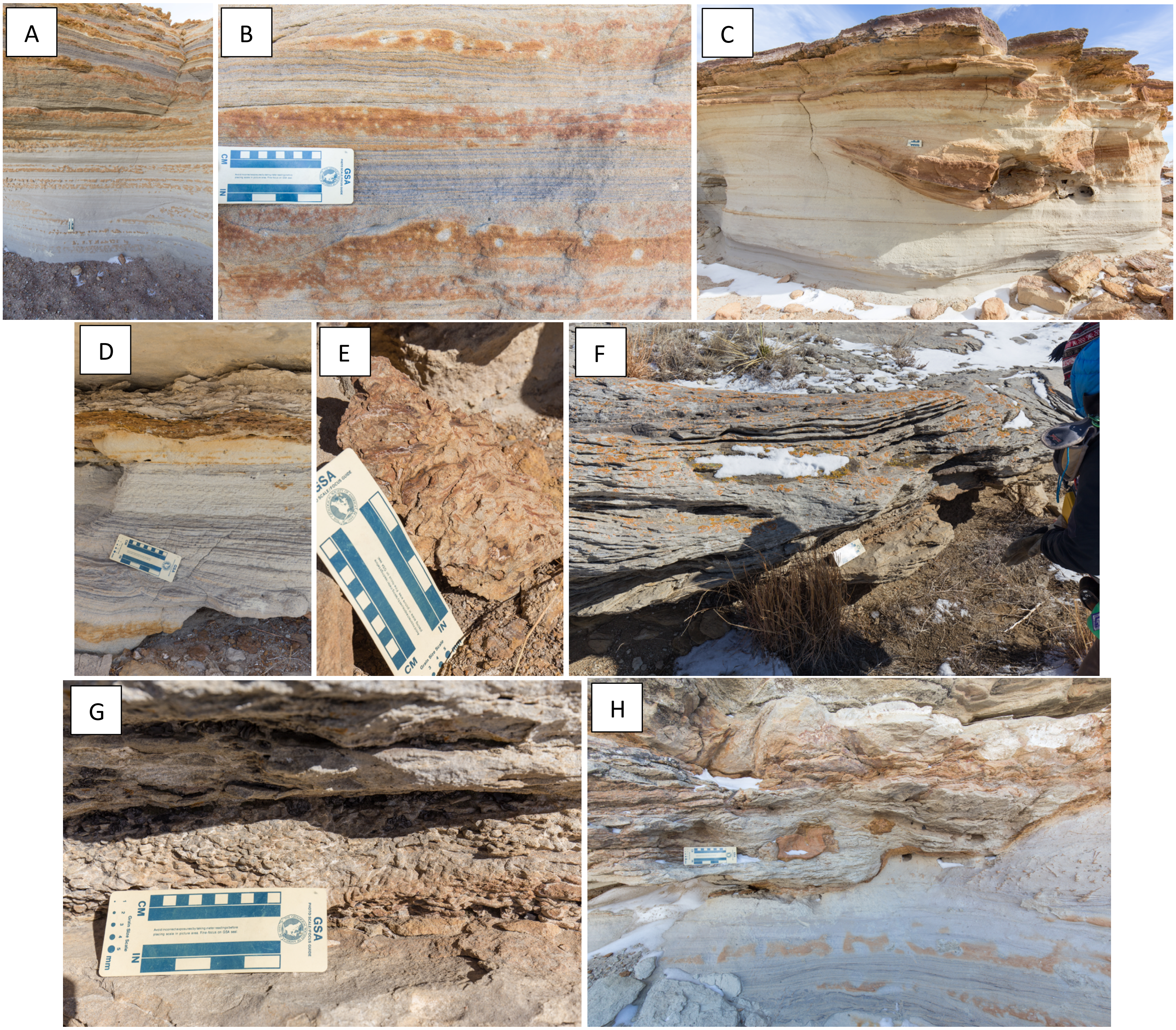


Figure 13b. *Photos of Fox Hills Sandstone at Titanium Ridge, Colorado. Scale card in all photos is ~16.5 cm (6.5 inches) long. (A) The north end of Titanium Ridge near TR-13 – cut-and-fill channel in upper foreshore deposits overlain by heavy-mineral-rich laminae deposited in the backbeach; (B) Heavy-mineral laminae in the same area as A; (C) Upper foreshore sandstones (heavy-mineral-poor) with cut-and-fill structures on the south end of Titanium Ridge – upper oxidized portion contains heavy-mineral-rich layers; (D) Heavy-mineral laminae with overlying heavy-mineral-poor sandstone, overwash deposits containing layer of organic material, and lithified gray sandstone caprock; (E) Fossil plant remains in the organic material from D; (F) Long wavelength crossbedding in upper sandstone with underlying layers containing horizontal burrows; (G) Close-up of horizontal (bedding plane) burrow layer mentioned in F; (H) Fox Hills Sandstone at TR-14 showing heavy-mineral laminae and overwash deposits.*

regression of the interior seaway" (Raynolds, 2002, page 114). It forms a series of "*off-lapping*" sandstone bodies that were deposited in nearshore and beach environments (Dechesne and others, 2011). Retreat of the WIS to the east deposited a succession of climbing sandstone sets (i.e. "*shingles*") or shoreface sequences that decrease in age upward and step up to the east (Dechesne and others, 2011) (Figure 10). These consist of well-sorted, medium- to fine-grained, quartz-dominant sandstone beds, ~10 to 15 m (~30 to 50 ft) thick, with *Ophiomorpha* trace fossils and planar crossbedding (Raynolds, 2002). Due to this offlapping pattern of individual sandstone bodies, the Fox Hills Sandstone does not form a continuous surface and its individual sandstone bodies range between 9 and 30 m (30 and 100 ft) thick (Dechesne and others, 2011). Also, due to the

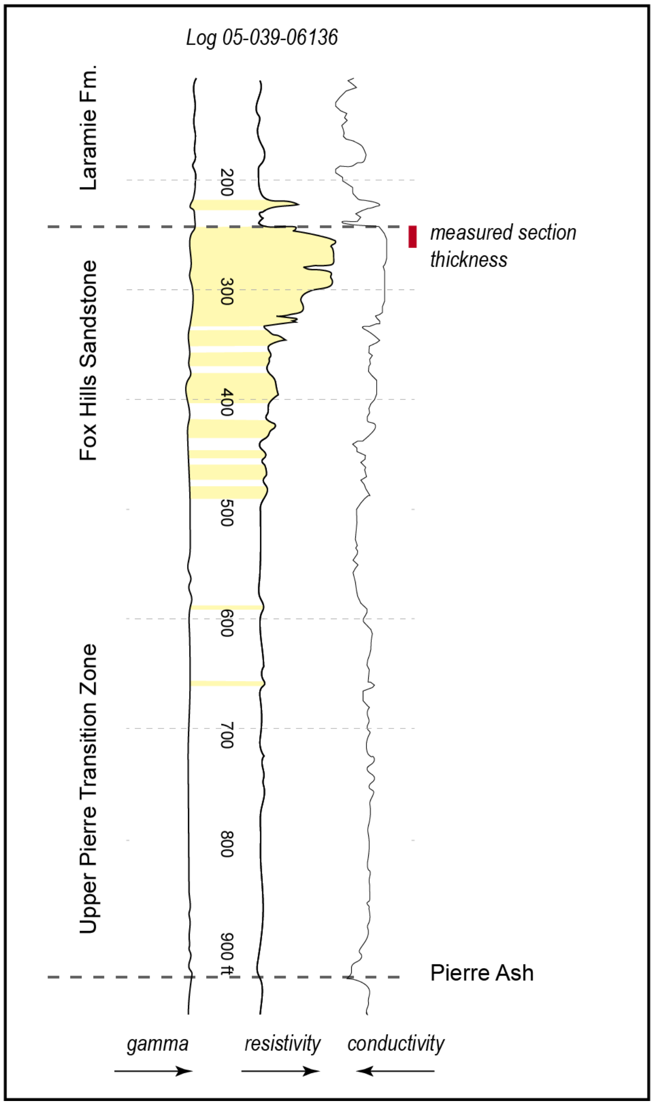


Figure 14. *Subsurface geophysical log example from the eastern Denver Basin, Colorado. The measured section location from this investigation is shown in red. Yellow represents sandstone. Fm. = formation. Depth in feet. Modified from Dechesne and others, 2011.*

shingled nature of the Fox Hills Sandstone, marine shale associated with the Pierre Shale has intertongues above and below the sandstone (Raynolds, 2002). In some cases, facies of the Laramie Formation (e.g., coal beds or carbonaceous shales) are observed between the individual shoreface deposits typically associated with the Fox Hills Sandstone (Dechesne and Raynolds, 2010) (Figure 10).

Because the Fox Hills Sandstone was deposited along the receding WIS during the Late Cretaceous, it can be used to reconstruct the paleoshorelines, or strandlines, during this time in the eastern Denver Basin. Dechesne and Raynolds (2010) identified at least 12 linear beach ridges with a maximum mapped strike length of over 250 km (~150 miles) and an average width of 8 to 10 km (~5 to 6 miles) each, interpreted from a dataset of over 1,350 geophysical logs. These paleoshorelines are generally linear, suggesting longshore currents; however, occasional embayments can also be mapped. The coastlines in the eastern part of the Denver Basin are younger than those to the west, spanning ~100 m (~330 ft) of stratigraphic section (Dechesne and Raynolds, 2010) (Figure 10).

Typically, the basal part of the Fox Hills Sandstone grades from centimeter-scale ripple beds, silt, and marine mudstones of the Pierre Shale to increasingly coarser and thicker-bedded, fine-grained sandstones of the Fox Hills Sandstone. This contact is not sharp and therefore a thickness for the Fox Hills Sandstone is difficult to determine. Usually, the contact between the Pierre Shale and Fox Hills Sandstone is identified as the point just below the lowermost sandstone bed of the latter unit, a point that varies somewhat across the basin. Available geophysical well logs from nearby oil and gas wells indicate that this contact is below the section studied during this investigation (Figure 14) and the thickness for the Fox Hills Sandstone from its lowermost sandstones to its top is ~75 m (250 ft) (Dechesne and others, 2011).

Bishop and others (2011) and Pirkle and others (2012) provide a description of the stratigraphy, facies, and modern analogs for the Fox Hills Sandstone in the study area. At least one of their stratigraphic sections was on a feature locally known as Titanium Ridge (Figure 1) and very close to a stratigraphic section measured during this study. Beach features reported by these authors include laminated heavy mineral placers, plant roots, wood fragments, and a sea turtle nest. The depositional model presented by Pirkle and others (2012, page 40) represents a *"prograding series of isochronous facies (Laramie-Fox Hills-Pierre) that were modified by episodes of transgression resulting in the formation of beach placers on coastal barrier islands."* They report a stratigraphic sequence from Titanium Ridge containing the following facies, from the top to the bottom: eolian facies; covered interval—possible paleosol; washover fan; backbeach; and foreshore (shallow subtidal) (Bishop and others, 2011; Pirkle and others, 2012).

The backbeach facies is reported to contain ripple marks, *Scolithos*, root traces, and a sea turtle nest (Bishop and others, 2011; Pirkle and others, 2012). At other outcrops of Fox Hills Sandstone in the area, these authors observed two or three episodes of colonization by *Ophiomorpha* suggesting periods of shoreline migration with possible stillstands, or fluctuations. Pirkle and others (2012, page 39) also suggest that the stratigraphic section at Titanium Ridge may be the result of *"two intermittent transgressive pulses in a prograding coastal plain environment"* and make analogs to modern and ancient beaches observed on St. Catherines Island, Georgia. Other modern analogs for Cretaceous beach placer deposition in the western U.S. are presented by several authors and include the Northern Gulf of Mexico, especially along the Texas coastline (Jacka, 1970), Sapelo Island in Georgia (Howard and Scott, 1983; Roehler, 1989), and the Gulf Coast of Mississippi, and Apalachicola, Florida (Roehler, 1989).

PREVIOUS MINERAL EXPLORATION ACTIVITIES

Exploration projects completed near or within the study area concentrated on uranium, coal, and heavy minerals including titanium, garnet, and zircon. A timeline of exploration activities is included as **Table 2**. Coal exploration focused on the Laramie Formation and heavy mineral exploration focused on the Fox Hills Sandstone. The coal exploration is discussed here due to the occurrence near the heavy minerals (e.g., reportedly overlying in some cases). Future economic studies or mining activities may have to address the mineral rights associated with both the coal and beach placers.

Table 2. *Summary of exploration activities timeline near Titanium Ridge, Colorado.*

1956	Airborne radiometric surveys conducted by the Atomic Energy Commission (AEC) to identify uranium deposits in portions of Colorado, including the Denver Basin.
1965	AEC report indicated several radiometric anomalies associated with beach placers near what is known locally as Titanium Ridge (Malan, 1965).
1960s - 1970s	Uranium exploration in the area.
1970	Houghton and Murphy (1970) provided a general location map of a beach placer location west-northwest of Limon, Colorado.
1975-1981	Rocky Mountain Energy (RME) conducted a four-stage coal exploration project in the overlying Laramie Formation (> 58,000 feet of drilling at > 500 holes). Drilling data extend from the Laramie Formation into the top of the Fox Hills Sandstone where the beach placers were reported.
1977	Houston and Murphy (1977) provided a general location map, host formation name, and strandline trend associated with the "black sandstone" deposit near Limon.
1983	AEC made 1965 report available, identifying thorium and other mineral bearing paleoplacers near Titanium Ridge.
1992	Exploration for proppant sand by private parties detected elevated concentrations of heavy minerals (e.g., ilmenite, zircon, and garnet) in the Fox Hills Sandstone.
1995 - 1996	Riverbend Exploration Inc. (Riverbend) was incorporated in 1995 following additional sampling and analysis after 1992; Riverbend then acquired mineral leases in the area, and entered into an exploration agreement with DuPont.
1997 - 1998	DuPont completed 206 drill holes over a north-to-south distance of ~77.2 km (48 miles). Mineralized sands were identified in subparallel trends over about 155 square km (60 square miles). Sea turtle nesting structures were reported in 1997 near the north end of Titanium Ridge.
Post 1998 - 1999	Riverbend entered into a joint venture agreement with Radar Acquisitions Inc. (Radar). This joint venture included the completion of 91 drill holes totaling 1,690 m (5,545 ft) within the Riverbend mineral lease and on other properties through an agreement with Union Pacific Railroad exploration (UPRe) and others. A ground magnetic survey was completed in a smaller area to the east of I-70, along the western beach placer trend, and included 15 geophysical transects. In 1999, bulk samples were sent to laboratories for processing tests.
2000	In January, Radar acquired Riverbend as a wholly owned subsidiary (the mineral leases are held by Riverbend). In August, Radar completed a study on the property to the west of I-70, along the western beach placer trend, that included an estimate of potential resources based on drilling and geophysical surveys. That report focused on titanium minerals, garnet, and zircon resources in beach placers along the western beach placer trend.
2001 - 2003	Radar provided an update to the original estimate of potential resources along a portion of the western beach placer trend in terms of the contents of saleable minerals rather than total heavy minerals. They also provided a confirmation of the resources by an independent qualified person (dated 23 November 2003). In 2002, an initial coal evaluation report associated with the overlying Laramie Formation was completed for a larger area, containing much of the heavy mineral deposit (Smith, 2002).
2007	Radar provided a NI 43-101 technical report on coal deposits in the Laramie Formation (Tetra Tech, 2007).
2011 and 2012	Additional reports completed that document sea turtle nesting structures at Titanium Ridge, heavy sand deposits, stratigraphy, comparison to other heavy mineral deposits located in the southeastern U.S., and comparison to barrier island depositional environment on the east coast of the U.S.
2017	Colorado Geological Survey (CGS) evaluated the Fox Hills Sandstone for proppant sand potential.
2018 - 2019	CGS conducted field reconnaissance of beach placers in the Fox Hills Sandstone and collected samples for laboratory analysis.

NOTES: CGS - Colorado Geological Survey, NI - national instrument (of Canada), UPRe - Union Pacific Railroad exploration

URANIUM EXPLORATION

In the 1950s and 1960s, several radioactive heavy mineral deposits were discovered in Upper Cretaceous rocks during the search for uranium in Colorado, New Mexico, Utah, and Wyoming (Dow and Batty, 1961). Additionally, in eastern Colorado, previous exploration activities targeted uranium deposits in the Fox Hills Sandstone and Laramie Formation. In 1956, several airborne radiometric anomalies were reported near Limon during an Atomic Energy Commission (AEC) study of uranium deposits in Colorado (see map provided in **Appendix A**) (Malan, 1965). An evaluation of these anomalies determined that there was a potential low-grade thorium resource, likely related to monazite, in paleobeach placers at Titanium Ridge (Figure 1). However, the paleoplacer deposit was described as occurring in sandstones in the lower portion of the Laramie Formation, which is now considered part of the Fox Hills Sandstone due to its beach and shallow marine depositional facies. The following description of an outcrop, reported to occur near where the railroad cuts (Appendix A – see map of original 1956 AEC Survey - just north of the cross-section line) the Laramie Formation – Fox Hills Sandstone contact, was provided in this report:

> *"…..a mineralized sandstone bed averaging four and one-half feet thick is underlain by the basal unit of the Laramie, a crossbedded, friable, gray to white sandstone at least 12 feet thick. A calcareous sandstone, one and one-half feet thick, overlies the mineralized bed and caps the outcrop. Nearby, there are exposures of lignitic coal interbedded with sandstone overlying the calcareous sandstone……..The mineralized bed is a brown to black friable sandstone that contains abundant heavy refractory minerals that were deposited as an ancient beach placer. The heavy minerals are concentrated along thin bands separated by sandstone containing lesser amounts of heavy minerals. Heavy minerals including garnet, zircon, magnetite, and ilmenite make up as much as 75 percent of the mineralized bed. Uranium and thorium contents are rather constant and average 0.007 percent U_3O_8 and 0.08 percent ThO_2…….All are beach concentrates overlain by coal-bearing lagoonal sediments in a regressive sandstone series of the Upper Cretaceous. Also, all trend north-northwest parallel to strand lines" (Malan, 1965, page 89).*

The 1956 AEC anomalies were also reported to occur in other nearby areas by the CGS (Nelson-Moore and others, 1978). Shallow drilling was completed at one anomaly and observed minerals include garnet, zircon, and magnetite concentrated in *"thin bands separated by sandstone with lesser amounts of minerals"* (Nelson-Moore and others, 1978, page 139).

COAL EXPLORATION

Coal mining took place to the west of Limon between 1921 and 1951 in an area known as the Buick-Matheson coal region. Historical coal (i.e. lignite) production in this area was from the Laramie Formation and totaled ~96,800 metric tons (106,740 short tons) (Kirkham and Ladwig, 1980). The area associated with this study includes a portion of the Buick coal region. Coal exploration projects were completed in the Buick, Matheson, Deer Trail, and other coal regions to the east of Limon in the mid-1960s through the 1980s.

Prior to 1992, exploration activities in this general area concentrated on coal resources. Since the 1970s, a portion of the study area consisted of several coal leases and exploration projects referred to by several names including the Buick Project, Buick Coal Project, Limon Lignite Property, Limon Coal Project, and Buick Coal/Power Project. Between 1975 and 1981, an extensive exploration drilling program was carried out in the area by Rocky Mountain Energy (RME), the exploration arm of the Union Pacific Railroad (UPRe) (RME, 1975; Smith, 2002; Tetra Tech, 2007) and later known as Union Pacific Resources Group, which later in 2000 merged with Anadarko. A four-stage coal exploration project was conducted during this time and included a total of ~17,400 m (~57,380 ft) (419 holes) of rotary drill holes and ~345 m (1,135 ft) (83 holes) of core drilling (Tetra Tech, 2007). Between 2004 and 2007, several studies were completed by Radar Acquisitions Inc. (Radar) and partners to assess the coal resources on their property which was once marketed as a combined coal and titanium/zircon/garnet resource. A Canadian National Instrument (NI) 43-101 technical report on the coal deposit (beach placers were addressed in a different report) was completed by Tetra Tech (2007) and summarizes the history and resources associated with the coal deposits in the overlying Laramie Formation (Tetra Tech, 2007).

BEACH PLACER DISCOVERY, EXPLORATION, AND ASSESSMENT

During a statewide reconnaissance study for hydraulic fracturing sand sources in 2017 (O'Keeffe and others, 2018), the CGS observed a surface exposure of Upper Cretaceous Fox Hills Sandstone containing a beach placer near Limon, CO. Preliminary mineralogical analysis of a sample of a beach placer sample collected on Colorado State Land Board (SLB) property in 2017 detected 6.7% ilmenite, 2.2% rutile, and 1.4% zircon (vol. %). These results prompted the CGS to conduct additional research as summarized below.

As previously reported, beach placers in the area west of Limon were first mentioned by Malan (1965) (Appendix A). Other later publications from the 1970s (Houston and Murphy, 1970; Houston and Murphy, 1977) provide general location maps, the north-northwest paleoshoreline trend associated with the beach placers, and a relative Late Cretaceous Maastrichtian age (72.1 to 66 Ma) (Houston and Murphy, 1977; Walker and others, 2018). The first mention of *"Titanium Ridge"* was in 2012 and refers to a ridge where a portion of the beach placer in the Fox Hills Sandstone is exposed at the surface (Pirkle and others, 2012) as shown in previous studies (Malan, 1965). The location of Titanium Ridge is shown in **Figures 1 and 15**.

Exploration activities in the 1990s concentrated on potential economic beach placer deposits of titanium-bearing minerals, garnet, and zircon associated with the Fox Hills Sandstone in this area (WGM, 2000; Pirkle and others, 2012) (Table 2). The 1990s exploration activities included drilling, sampling, an aeromagnetic survey, ground-based magnetic surveys, and a report that provides an estimate of potential resources along a portion of the western beach placer trend (WGM, 2000; Radar, 2001; Pirkle and others, 2012).

Radar performed exploration activities, known as the Riverbend project, in the area. Their economic assessment and subsequent report focused on beach placers (WGM, 2000; Radar, 2001) associated with a paleoshoreline trend referred to as the western beach placer trend, or western trend, in this report and shown on Figures 1 and 15. Before Radar's proj-

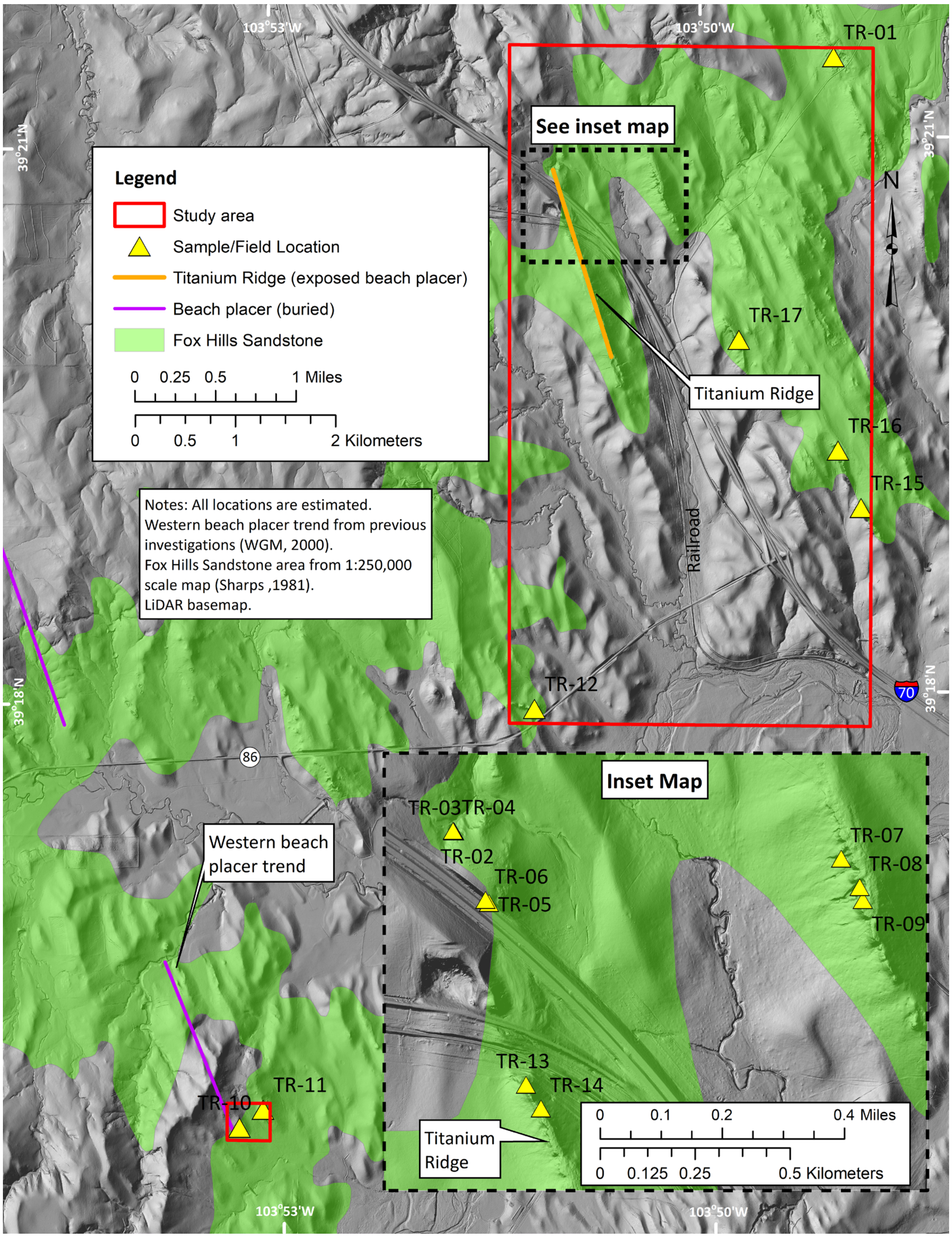


***Figure 15.** Sample location map, Titanium Ridge area, Colorado.*

ect, Riverbend Exploration Inc. (Riverbend), incorporated in 1995, had acquired mineral leases in this area and entered into an exploration agreement with E.I. du Pont de Nemours and Company (Dupont) in 1996. Between 1997 and 1998, Dupont drilled 206 holes over a north-south distance of ~75 km (~50 miles) in the area. Riverbend subsequently entered into a joint venture agreement with Radar. This joint venture included the completion of an additional 91 drill holes within the Riverbend mineral lease and on other properties through an agreement with UPRe and others. A ground magnetic survey was also completed along the western beach placer trend and included several geophysical transects. Drilling in the 1990s focused on this area as well as on testing geophysical anomalies along the western beach placer trend projection to the north (WGM, 2000) (Appendix A).

Although Radar focused their economic assessment on a portion of the western beach placer trend, some exploration activities were conducted at other beach placers (WGM, 2000; Pirkle and others, 2012) that occur along other subparallel paleoshoreline trends in the Fox Hills Sandstone. Additional geophysical and/or subsurface exploration was carried out in several other areas including Titanium Ridge, trends to the east of Titanium Ridge, projections of these trends ~65 km (40 miles) to the north of Titanium Ridge, and a trend ~10 km (7 miles) south of the western beach placer trend and on the south side of the Big Sandy River (WGM, 2000). Although analysis of the DuPont drilling results suggested the presence of additional resources in areas besides the western beach placer trend, the scope of Radar's project was to *"demonstrate continuity in three dimensions in a portion of the deposit large enough to be potentially economic"* (WGM, 2000, page 5) and therefore, Radar only reported the potential mineral resources along the western trend.

The available reports that summarize the findings of the late-1990s exploration in this area indicate the following (WGM, 2000; Pirkle and others, 2012).

- The beach placers form subparallel discontinuous beach strandlines near the top of the Fox Hills Sandstone; these crop out in the area and in exploration holes have been traced into the subsurface, downdip to the northwest, to a depth of ~45 m (150 ft).
- The subparallel beach placers follow northwest-striking trends over an area of ~95 km (60 miles).
- The western beach placer trend was traced for at least ~25 km (14 miles) using aeromagnetic survey data, and drilling activities were identified as extending in the subsurface over a distance of ~10 km (7 miles) (WGM, 2000; Pirkle and others, 2012).

As reported by Radar, portions of the Fox Hills Sandstone along the western beach placer trend contain heavy mineral concentrations ranging from greater than 3 to 50%, thicknesses reportedly up to ~15 m (45 ft) thick, with an average of ~5 m (17 ft) (based on an analysis of Radar's cross sections), and widths up to ~370 m (1,200 ft) (WGM, 2000). Radar's aerial magnetic surveys suggest that the heavy mineral deposits in this area may have strike lengths of ~40 km (24 miles) and widths between 300 and 730 m (~980 and 2,390 ft) (Pirkle and others, 2012). Paleoshoreline trends in this area previously were reported as north-northwest (Houston and Murphy, 1977), and this orientation was confirmed by Radar. The paleoshoreline generally trends N 20° W along beach strandlines/offshore bars (WGM, 2000; Pirkle and others, 2012).

Analysis of a bulk sample collected during previous exploration activities detected elevated concentrations of garnet, ilmenite, zircon, sphene or titanite, epidote, allanite, monazite, and other minerals as summarized in **Table 3**. Radar concentrated on the titanium (dominantly ilmenite with some rutile), garnet, and zircon resources. A summary of their mineral resource estimate is included in **Table 4**. Their evaluation estimated a combined measured and indicated resource of 14.2 million tons containing an estimated 2.3% ilmenite, 0.1% rutile, 0.5% zircon, and 2.9% garnet based on bulk sample analysis (Figure 15, Table 4) (WGM, 2000). Estimated total heavy minerals ranged from 6.8 to 12.3%. An additional inferred resource was estimated to include another 3.3 million tons at various grades (**see Tables 4 and 5**) (WGM, 2000; Radar, 2001).

Table 3. *Heavy-mineral content of a bulk sample collected from the Fox Hills Sandstone, western beach placer trend near Limon, Colorado.*

Mineral	Weight Percent
Garnet	36.9
Ilmenite	29.3
Other	11.7
Zircon	6.5
Sphene (titanite)	4.9
Epidote	3.5
Allanite	3.2
Rutile	2.2
Monazite	0.9
Iron Oxides	0.6
Chromite	0.2
Chrome-Spinel	0.1
Perovskite	0.1
Corundum	0.1

Notes: After WGM (2000). Bulk sample is a composite sample of saved splits from mineralized intervals of drillholes along the length of the deposit identified along the western beach placer trend.

In 1999, bulk samples from the western beach placer trend were analyzed for processing tests including extraction tests for ilmenite, zircon, and garnet, as well as leachability tests on the ilmenite to produce synthetic rutile (WGM, 2000). Beneficiation tests indicated poor recovery of ilmenite, zircon, and garnet. Preliminary designs indicated that the conversion of ilmenite to synthetic rutile may benefit future development of this potential resource (WGM, 2000).

Table 4. *Summary of mineral resource estimates for the western beach placer trend near Limon, Colorado.*

Resource Type	Mineralized Sand (million short tons)	In-Ground Averages (weight %)			
		Ilmenite	Rutile	Garnet	Zircon
Measured	7.2	2.2	0.1	3.1	0.5
Indicated	7.0	2.3	0.1	3.0	0.5
Inferred	3.3	2.4	0.1	3.1	0.5

Notes: Values after Pirkle and others (2012), resources estimated by WGM (2000). These estimates are for a portion of the western beach placer trend (see text) located in: Sections 5 and 16, T9S, R58W; Section 32 T8S, R58W. Grades extrapolated from bulk sample, based on a cut-off grade of 1% total heavy minerals.

Table 5. *Detailed mineral resource estimate for the western beach placer trend near Limon, Colorado.*

Category	Section	Potential Resource (mineralized sand) (tons*) (millions)	Grade - Total Heavy Minerals (%)	Estimated from Bulk Sample			
				Ilmenite	Rutile	Zircon	Garnet
Measured							
	16	3.8	7.0	2.0%	0.1%	0.4%	2.6%
	5	3.4	8.2	2.4%	0.1%	0.5%	3.1%
	32	-	-	-	-	-	-
Subtotal		7.2	-	2.2%	0.1%	0.5%	2.8%
Indicated							
	16	1.0	12.3	3.6%	0.2%	0.8%	4.6%
	5	3.7	6.8	2.0%	0.1%	0.4%	2.5%
	32	2.3	9.0	2.6%	0.2%	0.6%	3.4%
Subtotal		7.0		2.3%	0.1%	0.5%	3.0%
Measured / Indicated - Combined							
	16	4.8	8.1	2.4%	0.1%	0.5%	3.0%
	5	7.1	7.5	2.2%	0.1%	0.5%	2.8%
	32	2.3	9.0	2.6%	0.2%	0.6%	3.4%
Total		**14.2**		**2.3%**	**0.1%**	**0.5%**	**2.9%**
Inferred							
	16	0.5	4.8	1.4%	0.1%	0.3%	1.8%
	5	2.0	9.4	2.7%	0.2%	0.6%	3.5%
	32	0.8	7.6	2.2%	0.1%	0.5%	2.8%
Subtotal		3.3		2.4%	0.1%	0.5%	3.1%

Notes: Assumed to be short tons - not specified in report - pounds and cubic feet are used in the tonnage factor calculation. Table after WGM (2000) - these data were released after the original WGM report and are included as an attachment to that report dated April 6th, 2001. Estimates based on 1% total heavy mineral cut-off grade over a minimum 5 feet drillhole interval and a tonnage factor of 14 cubic feet per ton. Grades extrapolated from a bulk sample analysis and therefore, are subject to scrutiny. Resource estimates are for a portion of the western beach placer trend located in: Sections 5 and 16, T9S, R58W; Section 32, T8S, R58W.*

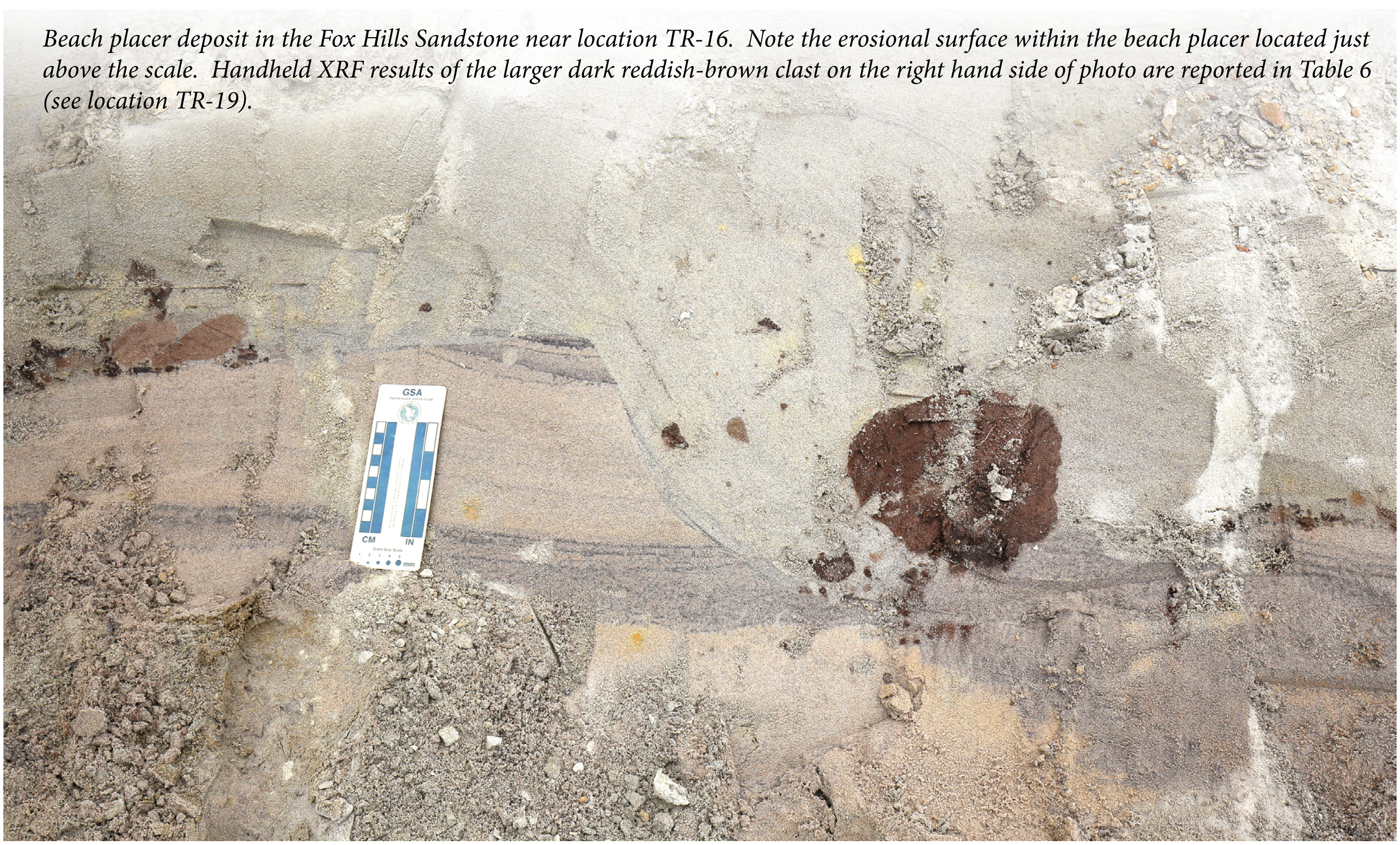
INVESTIGATION

This study concentrated on the Titanium Ridge area, but other Fox Hills Sandstone outcrops in the area were also described and sampled (Figure 15). Outcrops of the beach placers are limited and were observed along Titanium Ridge, along Interstate 70 (I-70) north of Titanium Ridge, on two hillsides north of the I-70 outcrop, and in an area south of Highway 86 and ~8 km (5 miles) southwest of Titanium Ridge (Figure 15). A photo log of sampling sites is included as **Appendix B**. The following sections discuss the stratigraphy, sample collection, and results of the laboratory tests performed during this investigation.

STRATIGRAPHY

Fox Hills Sandstone crops out below Cedar Point (elevation 1,826 m [5,991 ft] above mean sea level) (Figure 8), forms linear ridges that can be traced for several kilometers, and strikes approximately north-northwest. These linear ridges can be seen in the lidar base map in Figure 15. A cross section and location map of stratigraphic sections and beach placers is included in **Appendix C**. Detailed stratigraphic sections were measured along and near Titanium Ridge at locations TR-04, TR-05, TR-13, and TR-14 as shown on Figure 15. Observations focused on grain-size variations, sedimentary structures, and concentrations of heavy minerals along and near the ridgeline. The stratigraphic sections at Titanium Ridge are approximately 3 to 4 m (~10 ft) high and are included in Appendix C. Facies relationships between the sections associated with heavy mineral occurrences is shown in **Figure 16**. Panorama photographs of sample site outcrops at and near Titanium Ridge are included as **Figures 17, 18, and 19**. Additional stratigraphic sections were described at several locations and the notes are included in Appendix C.

Only the upper portion of the Fox Hills Sandstone is exposed along Titanium Ridge. The basal transitional part of the contact between the marine Pierre Shale and Fox Hills Sandstone was not exposed in the outcrops evaluated. From satellite imagery and elevations obtained from lidar data, the measured sections at locations TR-04, TR-05, just east of I-70, and TR-14 and TR-15, on the west-side of I-70, are apparently part of the same ridge (see cross section in Appendix C). Therefore, the differences between the localities show lateral variations in the littoral depositional environment rather than differences through time. The following subsections discuss these stratigraphic sections in detail.



Beach placer deposit in the Fox Hills Sandstone near location TR-16. Note the erosional surface within the beach placer located just above the scale. Handheld XRF results of the larger dark reddish-brown clast on the right hand side of photo are reported in Table 6 (see location TR-19).

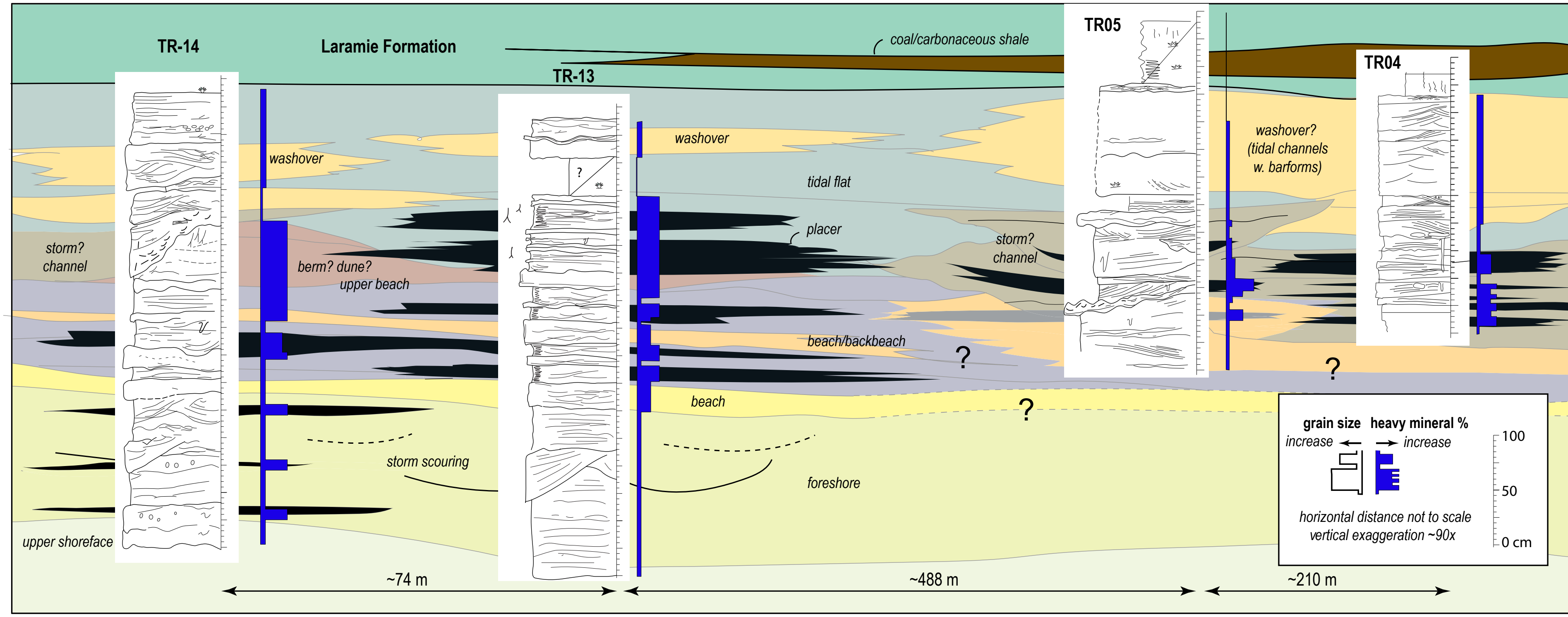
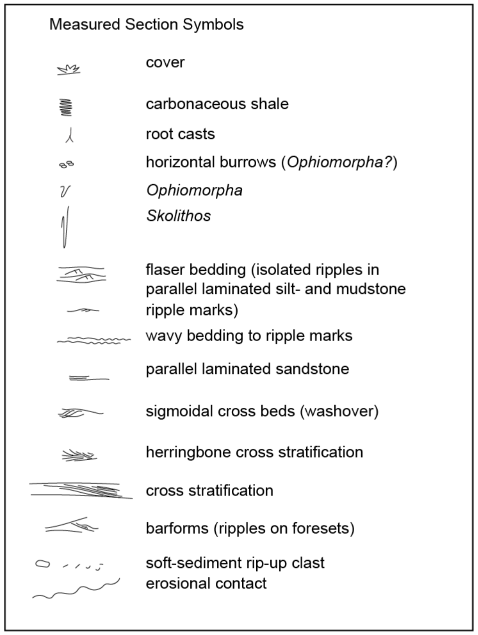


Figure 16. *Facies relations and heavy-mineral occurrences in the Fox Hills Sandstone between measured sections along strike, Titanium Ridge, Colorado. Heavy-mineral content and grain size vertical graph is shown for reference purposes only – details are presented on the full stratigraphic columns included in Appendix C .*



Stratigraphic Sections

Exposures at locations TR-13 and TR-14 (Figure 15; measured sections TR-13 and TR-14 in **Appendix C**) are located west of I-70 on Titanium Ridge. The exposures consist of upper and lower fine-grained, well-sorted, angular to subangular or subangular to subrounded sandstones. The sandstones have both parallel bedding and low-angle crossbedding and also common, up to several meters wide and up to 1.5 m (~5 ft) deep, erosional scours (Figure 13b, see photo C), filled with swaley cross stratification. Swaley cross stratification suggests deposition within the storm wave base, near the middle shoreface (Clifton, 2006), and the deep scours likely resulted from erosion during storm events. In the middle portion of the TR-13 measured section and the lower portion of TR-14, bands of dark gray sandstone occur with heavy mineral concentrations generally between 3 and 5%. The scours at both sections vary in width between 0.5 and 3 m (~1.5 and 10 ft) and decrease in size upward. Swaley cross stratification indicates a depositional

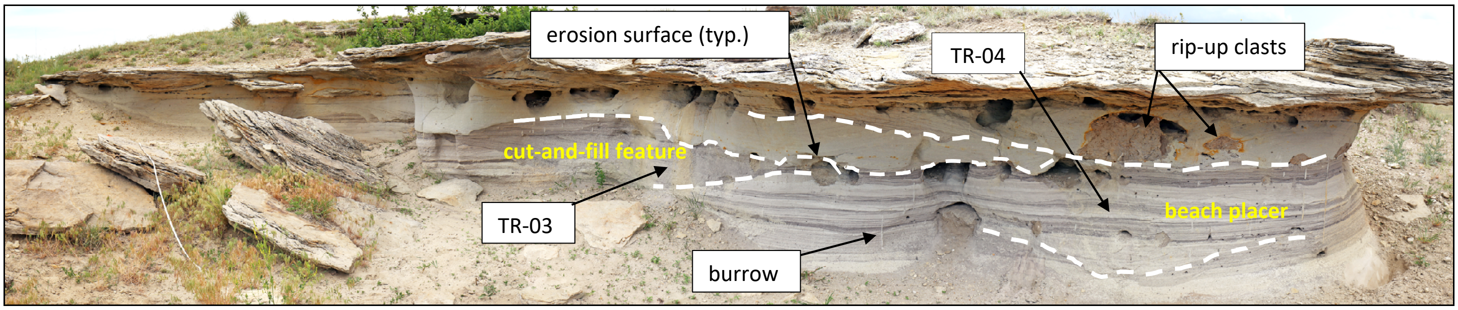
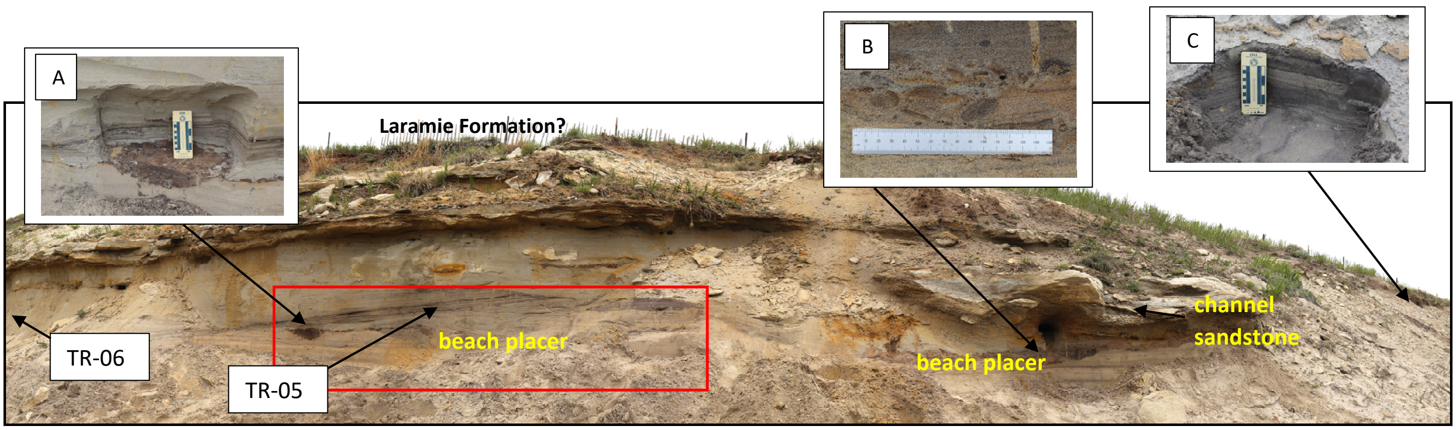


Figure 17. *Annotated panorama photo of the Fox Hills Sandstone at locations TR-03 and TR-04, Titanium Ridge area, Colorado. Beach placer contains abundant alternating bands of light and heavy minerals, vertical burrows (Ophiomorpha and what appear to be abundant skolithos – white vertical lines in photo), cut-and-fill features, several erosional surfaces, and rip-up clasts. Outcrop is approximately 2.6 m (8.5 ft) high.*



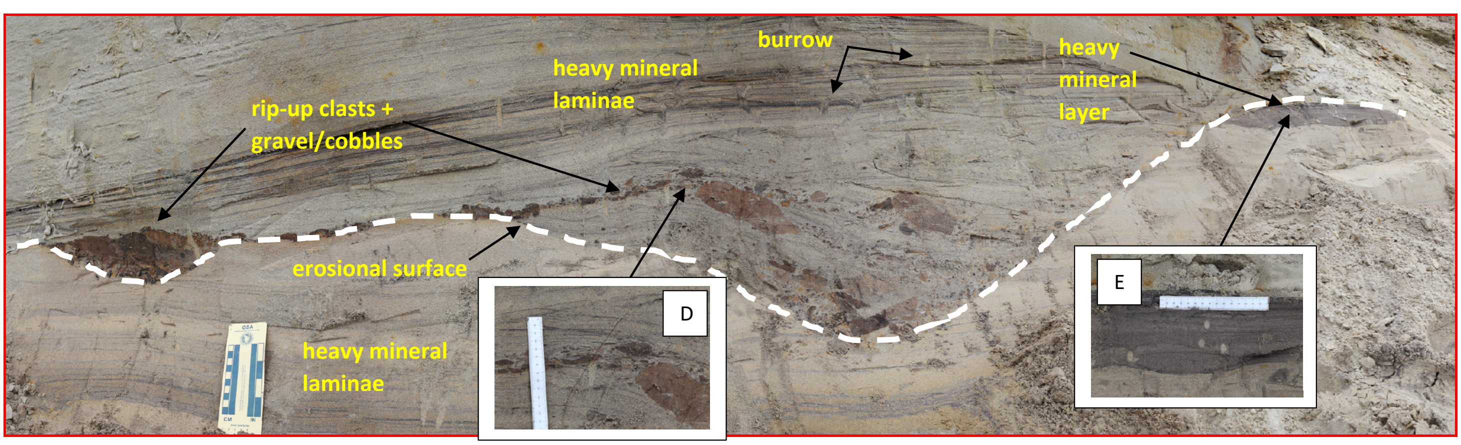


Figure 18. *Annotated panorama photos of the Fox Hills Sandstone at locations TR-05 and TR-06, Titanium Ridge area, Colorado (Note: TR-06 is off the photo to the left in the top picture). Top picture shows the outcrop at TR-05. Laramie Formation (buried) lies just below fence at the top of the photo. Outcrop is approximately 3.4 meters (11.2 ft) high. Bottom picture is a close-up of the red box in the top picture. Rip-up clasts are typically composed of heavy-mineral-rich sandstone fragments. A/B - Sandstone clasts in paleoswales. Scale in A is ~16.5 cm (~6.5 inches) long, scale in B is ~15 cm. C – Concentrated heavy-mineral laminae (same scale as A). D – Close-up of rip-up clasts (same scale as B). E – Concentrated heavy-mineral bed (same scale as B).*

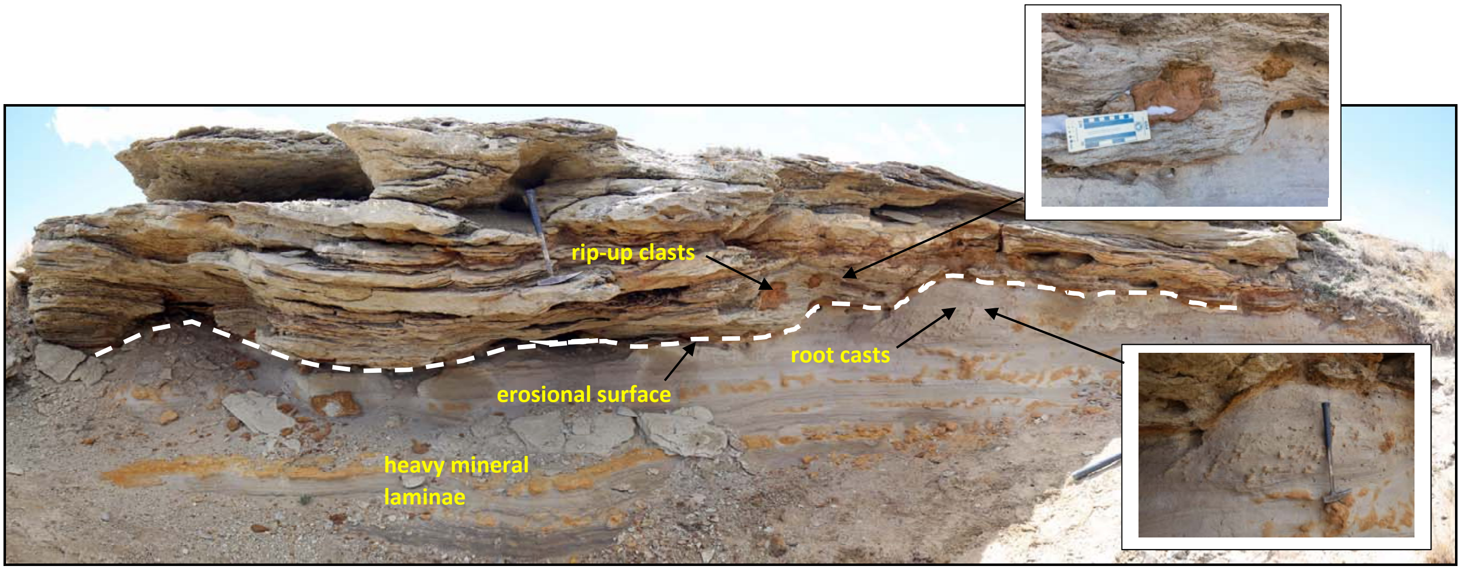


Figure 19. *Annotated panorama photo of the Fox Hills Sandstone at location TR-14 on Titanium Ridge near Limon, Colorado. Outcrop is ~ 2.5 m (8.2 feet) high, hammer is ~41 cm (~16 inches) long. Scale in top close-up of rip-up clasts is ~16.5 cm (6.5 inches). Hammer in bottom close-up picture is ~41 cm (~16 inches) long.*

setting proximal to the upper shoreface which is commonly impacted by storm scouring and wave influence. In the TR-13 section, bidirectional sigmoidal and tangential crossbeds occur above the interval of storm scours and the crossbeds are identical to sedimentary structures commonly observed in modern foreshore environments (Frey and Howard, 1988, their Figure 10; McGubbin, 1982). At TR-13, the swaley and scour-filled interval grades upward into parallel-bedded sandstones with alternating layers of concentrated heavy mineral beds up to 10 centimeters (cm) (4 inches) thick (Figure 13b, see photo A). Erosional incisions of 5 to 10 cm (2 to 4 inch) deep, ripple laminae, and *Ophiomorpha* burrows occur in this upper interval. The interval of alternating 5- to 10-cm (2- to 4-inch) thick heavy mineral and interbedded lighter mineral layers contains the highest concentrations of heavy mineral deposits observed in this section and corroborates a beach to backbeach depositional environment. Pirkle and others (2012) and Bishop and others (2011) documented sea turtle nests and trackways near this section and in the same interval also indicating a beach to backbeach depositional environment.

Rare root casts were observed at the 275-cm (~110-inch) interval at TR-14 (Figure 19; measured section TR-14 in Appendix C). The lack of distinct bedding in this interval and the presence of root casts (vegetation) suggest a depositional environment farther inshore and similar to the backbeach environment or farther inland. Subaerial sandstones (i.e. eolian deposits) are rarely preserved except in small wedges covered by storm washover fans (Asquith, 1970; Schwartz, 1982; Roehler, 1993). A 50-cm (20-inch)-deep erosional incision scours the root cast interval. The scour-fill contains coalified clasts, soft-sediment clasts, and wood fragments, as well as abundant tangential bedding in several distinct packages which are separated by finer-grained intervals (Figure 19). Erosional bases and tangential crossbedding sets observed at TR-14 appear similar to those found in modern hurricane washover deposits (Schwartz, 1982; Shaw and others, 2015). Near the Titanium Ridge ridgeline at this location, a ~5-cm (2-inch)-thick, carbonate-cemented, fine-grained sandstone bed caps the section.

East of I-70, stratigraphic sections at TR-04 (Figure 17) and TR-05 (Figure 18; measured sections TR-04 and TR-05 in Appendix C) are parallel bedded with concentrated heavy minerals (up to ~50%) laminae and fine-grained sandstone laminae (heavy mineral concentrations up to ~10%), and with abundant vertical *Skolithos* traces especially at TR-04 (see upper right hand photo in **Figure 20**). Crossbedding and pronounced erosional scouring were observed at TR-04. A layer with bidirectional sigmoidal crossbedding, suggesting tidal influence, is prominent at the top of the section (see photos 23 through 25 in Appendix B). The scour-filling unit contains soft-sediment rip-up clasts up to 90 cm (35 inches) in diameter and meter-scale crossbedding (Figure 17). Abundant rip-up clasts are present also at TR-05 within the beach placer deposits (Figure 18). At TR-04, the uppermost unit is carbonate cemented and resistant to weathering. The unit consists of fine-grained barforms with sigmoidal shapes, has ripple marks on foresets, and has only minor (~10%) heavy mineral content. Ripples in this unit appear sinuous crested in plan view. Carbonaceous shales of the Laramie Formation are above this unit as observed at TR-05 (Figure 18).

At TR-05, beach placers with fewer heavy minerals are overlain by beds containing more concentrated heavy-min-

Figure 20. *Trace fossils (burrows) in the Fox Hills Sandstone, Titanium Ridge area, Colorado. Upper left - Ophiomorpha burrows along Highway 86 west of Titanium Ridge. Upper right – vertical burrows at TR- 04. Bottom – Ophiomorpha burrows near TR-12. Hammer is ~41 cm (~16 inches) long.*

eral laminae (Appendix B, photos 40 and 41, contact of these beds is at the bottom of the scale in both photos). These two beds are separated by a sharp erosional surface where low points or swales are locally filled with heavy mineral-rich rip-up clasts (Figure 18). Some of these rip-up clasts are subangular to subrounded and appear imbricated (Figure 18, Appendix B – photos 35, 39, and 40). The erosional surface with rip-up clasts can be traced for over 15 m (49 ft) along the outcrop extending both northwest and southeast from TR-05, and the surface likely is storm related (Appendix B, photos 42 through 44 taken to the northwest of TR-05). The size of the storms would be difficult to determine, but some researchers report deposits having similar characteristics to those in the present study and suggest that they originate from tsunamis (Bondevik and others, 2005, their Figure 4A; Morton and others, 2007; Phantuwongraj and Choowong, 2012; Spiske and others, 2013). No attempt was made to determine if the physical properties of the Titanium Ridge deposits match the criteria used to identify tsunami deposits such as those presented by Morton and others (2007) and Peters and Jaffe (2010) or if they are typical for storm deposits associated with hurricanes (Shaw and others, 2015). Also, storm and tsunami deposits may appear similar as documented by others (Phantuwongraj and Choowong, 2012). In parts of the TR-05 exposure, the larger clasts appear to fill small (~30 to 75 cm; 11 to 30 inches) erosional depressions (Figure 18; Appendix B – photos 34 through 37, 43, and 45 through 49) suggesting that larger-sized material was transported onto the beach by larger waves and then trapped in low areas of the beach as water receded. At some locations, the rip-up clasts appear to be eroded in place indicating that this material was deposited during a single event. Images of a thin section from sample TR-05B containing rip-up clasts are included in Figure 26b (further on in this report) and **Appendix D**.

BEACH PLACER SAMPLE COLLECTION AND LABORATORY ANALYSES

Beach placers in the study area occur in a very fine to medium grained, well-sorted, subangular to subrounded, sandstone that ranges from weakly to moderately cemented. The beach placers contain local areas with abundant heavy-mineral laminae, bounded by sandstone with less disseminated heavy minerals. The Fox Hills Sandstone at sample locations TR-04 through TR-06 (Figure 15) is very friable, making it difficult to obtain intact samples for thin section without the sandstone disaggregating. Heavy minerals observed in the field using a hand lens are a variety of colors as shown in the photomicrograph of a sample from location TR-03B in **Figure 21**.

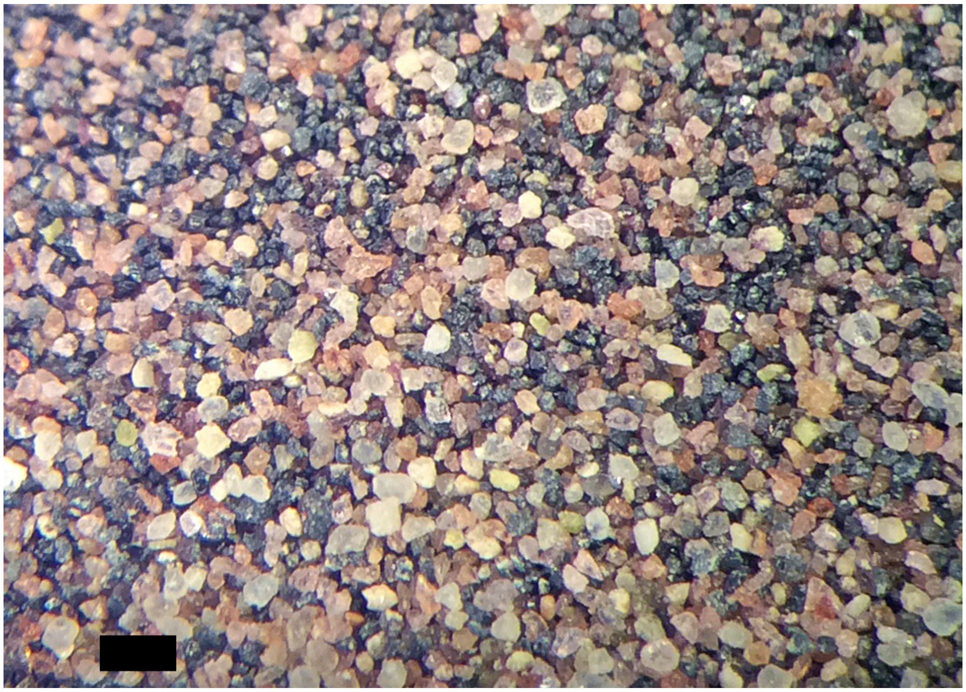


Figure 21. *Photomicrograph of heavy-mineral sand in the Fox Hills Sandstone from location TR-03B, Titanium Ridge area, Colorado. Long axis of black bar is 0.5 millimeters (~0.02 inches). Dominant heavy minerals include garnet, ilmenite, epidote, and zircon.*

Field screening of samples of the Fox Hills Sandstone was performed using a handheld Olympus Innov-X Delta Premium (DP-6000) x-ray fluorescence (XRF) analyzer. Samples were analyzed from the locations shown in Figure 15 and the screening results are summarized in **Table 6**. Additional samples were collected for laboratory analysis. Three vertical intervals at four locations (Figure 15, 12 samples from locations TR-03 through TR-06) within and adjacent to the exposed heavy-mineral laminae were sampled as summarized in **Table 7** and shown in **Figure 22**. These samples were analyzed in the laboratory using XRF and inductively coupled plasma mass spectrometry (ICP-MS) by the Peter Hooper Geoanalytical Laboratory at Washington State University. A summary of the laboratory XRF and ICP-MS results is included in **Tables 8 and 9**, respectively. Detailed photographs of the beach placer deposits observed in the field are shown in **Figure 23**.

Due to the friable nature of the Fox Hills Sandstone at the sample locations, care was taken to collect representative samples to keep the heavy-mineral laminae intact for thin section preparation. Thin sections were produced from the samples collected for laboratory analysis (12 samples from locations TR-03 through TR-06) at the Mines thin section laboratory. Due to the friable nature of the samples, the billets were impregnated with epoxy prior to thin section production. To determine their mineralogy, select Fox Hills Sandstone thin sections were analyzed by the Mines Mineral and Materials Characterization Facility, Department of Geology and Geological Engineering, using the Scanning Electron Microscopy (SEM)-based quantitative automated mineralogy system TIMA (TESCAN Integrated Mineral Analyzer). This facility includes a fully automated SEM-based analysis system that provides quantitative mineralogical and textural data on the basis of automated point counting. The instrument contains a custom-built electron-beam platform equipped with four energy dispersive x-ray spectrometers for mineral and compound identification within a wide range of sample types. A summary of the analysis is provided in **Table 10** and results of detailed scans in smaller areas are summarized in **Table 11**. Automated-mineralogy images of each full thin section are included in Appendix D and images for each detailed area are including in **Figures 24 through 27**. Additional detailed close-up automated-mineralogy images are also included in Appendix D.

SAMPLE FIELD SCREENING AND LABORATORY RESULTS

Results of the handheld XRF field screening detected elevated concentrations of titanium and zirconium (Table 6) at locations where heavy-mineral laminae were observed in the Fox Hills Sandstone. Higher concentrations of zirconium were detected in areas with higher titanium concentrations (**Figure 28**). Lower concentrations, at least an order of magnitude lower, were detected in underlying and overlying sandstone deposits where heavy-mineral laminae were absent and lower concentrations of disseminated heavy minerals were observed in the field (**Figure 29**). Generally, concentrations of strontium, thorium, uranium, and yttrium were also elevated by an order of magnitude in samples with visible heavy mineral laminations. Screening results also detected elevated concentrations of vanadium; however, laboratory analysis of these samples (discussed below) reported vanadium concentrations an order of magnitude lower than the field screening results.

Laboratory XRF analysis of Fox Hills Sandstone grab samples collected within the beach placer deposits (samples contain abundant heavy-mineral laminae) detected estimated TiO_2 concentrations ranging from ~8.1 to 11.5 wt. % (Table 8). Results of the ICP-MS analysis are summarized in Table 9. Laboratory analysis of the samples with heavy-mineral laminae detected elevated concentrations of zirconium and REEs (Table 9). The average zirconium concentration of all the samples is 13,059 parts per million (ppm); the 10

Table 6. *Summary of handheld XRF screening results of Fox Hills Sandstone samples collected in the study area.*

			Percent					Parts per Million							
Location	**Sample**	**Formation, HM Desciption**	**Fe**	**Al**	**K**	**Ca**	**S**	**Ti**	**Zr**	**Mn**	**V**	**Sr**	**Y**	**Th**	**U**
TR-01	TR-01	Fox Hills Sandstone, disseminated HMs	0.8	7.8	0.4	-	-	3,391	286	88	180	77	19	-	-
	TR-01	Fox Hills Sandstone, disseminated HMs	1.2	10.7	0.9	-	-	2,901	102	83	253	85	9	-	-
TR-02	TR-02	Fox Hills Sandstone, HM laminations	1.3	10.7	0.6	-	-	11,898	816	550	522	75	34	34	-
TR-03	TR-03A	Fox Hills Sandstone, disseminated HMs	2.0	4.8	1.8	-	-	9,881	1,857	708	518	90	64	95	31
	TR-03B	Fox Hills Sandstone, HM laminations	9.7	3.5	0.1	2.0	-	66,200	15,588	5,557	1,749	137	378	249	101
	TR-03C	Fox Hills Sandstone, HM laminations	8.2	3.6	0.2	1.8	-	56,800	12,352	4,626	1,319	126	313	209	78
TR-04	TR-04A	Fox Hills Sandstone, HM laminations	9.5	3.7	0.1	2.8	-	64,600	12,144	5,633	1,474	170	375	218	51
	TR-04B	Fox Hills Sandstone, HM laminations	7.4	3.7	0.4	1.3	-	48,900	9,702	4,002	1,418	126	288	163	57
	REF1	Fox Hills Sandstone, HM laminations	6.7	4.6	0.2	1.1	-	57,200	6,406	3,602	1,165	119	237	107	36
	TR-04C	Fox Hills Sandstone, HM laminations	7.6	2.8	0.2	2.2	-	48,300	9,391	4,040	1,445	149	317	198	71
TR-05	TR-05A	Fox Hills Sandstone, few laminae / disseminated HMs	2.0	3.7	1.6	-	-	10,827	2,816	887	453	98	74	121	27
	TR-05B	Fox Hills Sandstone, HM laminations	9.0	4.4	0.6	0.7	-	62,200	18,313	4,712	1,546	118	343	213	83
	TR-05C	Fox Hills Sandstone, HM laminations	7.6	4.3	0.7	0.1	0.1	53,600	15,267	3,638	1,211	115	258	226	59
	REF1	Fox Hills Sandstone, HM laminations	10.2	6.6	0.3	0.5	-	95,400	20,112	5,699	1,757	116	308	170	60
	REF2	Fox Hills Sandstone, HM laminations	4.9	9.2	1.0	-	-	45,860	10,588	2,552	1,335	105	214	153	37
TR-06	TR-06A	Fox Hills Sandstone, few laminae / disseminated HMs	2.4	4.4	1.3	-	-	13,405	2,972	1,170	561	105	97	115	25
	TR-06B	Fox Hills Sandstone, HM laminations	10.3	5.1	0.1	1.8	-	70,600	16,314	5,582	1,666	158	343	206	53
	TR-06C	Fox Hills Sandstone, HM laminations	9.2	3.9	-	2.5	-	65,200	13,132	5,112	1,886	157	345	217	81
TR-07	REF1	Fox Hills Sandstone, disseminated HMs	0.6	5.3	0.9	-	-	1,585	117	85	298	61	13	-	-
	REF2	Fox Hills Sandstone, laminated sandstone / micaceous black siltstone, HM poor	3.7	7.3	1.4	0.2	0.2	2,842	87	182	332	148	23	-	-
	REF3	Fox Hills Sandstone, carbonaceous clayey silt or silty clay with dark laminae, no apparent HMs	3.3	6.7	1.5	-	-	3,081	103	199	301	74	35	36	12
	REF3A	Fox Hills Sandstone, carbonaceous silty clay or clayey silt with dark laminae, no apparent HMs	2.7	7.2	1.5	0.2	0.1	2,670	143	215	293	103	28	34	-
	REF4	Fox Hills Sandstone, calcareous rock	0.6	2.7	0.1	37.8	-	1,312	26	4,640	-	172	21	48	-
TR-08	REF1	Fox Hills Sandstone, dark HM laminae	3.7	7.2	1.4	0.3	0.2	4,016	117	763	335	161	45	48	-
	REF2	Fox Hills Sandstone, disseminated HMs	0.9	7.4	1.4	-	-	1,355	76	77	-	90	15	33	-
	REF3	Fox Hills Sandstone, rip-up clasts of off-white clay or silt	2.4	4.4	0.4	36.2	-	1,923	63	5,570	399	163	81	42	-
TR-10	XRF	Fox Hills Sandstone, 0.18 m (0.6 ft) HM rich zone	15.7	6.0	-	2.6	0.1	106,300	12,720	8,561	3,455	182	382	511	50
TR-11	REF	Fox Hills Sandstone, HM poor, disseminated HMs	3.7	6.5	2.2	-	1.1	1,428	86	-	347	129	14	61	-
TR-12	REF1	Fox Hills Sandstone, disseminated HMs	8.7	5.1	1.3	-	3.1	2,156	112	-	-	165	17	59	-
	REF2	Fox Hills Sandstone, disseminated HMs	7.5	2.3	2.8	-	6.2	1,669	119	-	297	68	12	56	-
TR-13	REF1	Fox Hills Sandstone, HM laminations	15.3	6.2	-	1.2	0.5	137,000	23,697	7,438	2,284	180	317	398	97
	REF2	Fox Hills Sandstone, HM laminations	15.3	4.6	0.1	0.7	0.7	135,300	32,894	6,248	1,982	133	249	376	99
TR-14	REF1	Fox Hills Sandstone, HM laminations	8.0	6.8	0.1	2.0	0.4	78,000	8,294	3,528	1,307	162	160	268	40
TR-15	REF1	Fox Hills Sandstone, disseminated HMs	2.6	4.9	1.8	-	0.4	4,663	491	-	-	166	29	86	-
	REF2	Fox Hills Sandstone, likely lower transitional unit, shale or mudstone	2.3	9.5	1.4	-	0.1	3,646	149	-	270	81	28	36	-
TR-16	REF1	Fox Hills Sandstone, disseminated HMs	5.7	6.7	1.2	-	-	1,931	155	523	-	101	21	30	-
TR-17	REF1	Fox Hills Sandstone, disseminated HMs	0.8	5.1	1.1	-	-	1,113	81	76	247	85	16	20	-
	REF2	Fox Hills Sandstone, carbonaceous micaceous laminae	4.3	10.2	1.4	1.0	-	2,538	83	411	357	92	35	-	-
	REF3	Fox Hills Sandstone, disseminated HMs, trace faint laminae	0.8	7.3	1.5	-	-	1,617	80	-	-	79	14	45	-
TR-18	TR-18	Fox Hills Sandstone, 15.2 cm (6 inch) HM zone on south portion of I-70 outcrop	19.4	7.0	-	2.2	0.1	141,200	23,815	9,683	2,546	159	488	214	91
TR-19	TR-19	Fox Hills Sandstone, reddish brown rip-up clast from TR-05 outcrop area	4.5	5.7	0.2	-	-	52,226	10,443	2,218	779	68	101	88	34

Notes: All estimated results from handheld XRF. See Appendix C for detailed descriptions of the sample names beginning with "REF." HM - heavy minerals.

samples with abundant laminae have a zirconium average of 16,496 ppm. Total REE (TREE) concentrations detected by ICP-MS in the 10 samples with heavy-mineral laminae ranged between 3,302 and 4,909 ppm and averaged 4,187 ppm. Plots showing the relative concentrations of the REEs are shown in **Figures 30 and 31**. Analysis of the 10 samples with abundant heavy-mineral laminae detected elevated REE concentrations enriched in the LREEs ranging between 2,820 and 4,205 ppm with an average of 3,589 ppm. In these same samples, HREE concentrations ranged between 482 and 704 ppm with an average of 598 ppm. Generally, elevated concentrations of zirconium and TREEs were detected in samples with higher TiO_2 content (**Figure 32**). Order-of-magnitude increases of niobium, scandium, tantalum, thorium, and uranium were also detected in samples containing visible heavy-mineral laminae (Table 9).

Automated mineralogy analysis detected, on average, ~12.9 volume % (vol. %) titanium minerals in the Fox Hills Sandstone thin sections containing abundant heavy-mineral laminae (**Table 10**). Titanium minerals include ilmenite, rutile,

Table 7. Descriptions of Fox Hills Sandstone samples collected in the study area.

Location	Sample	Sample Interval[1]	Hand Sample Description	Comments
TR-03	TR03A	1.8-2.1	Fox Hills Sandstone, very fine to medium grained, subround to subangular, very friable, light gray, 60% quartz, trace potassium feldspar/plagioclase, trace fines (<10%), >10% disseminated black opaque minerals, trace reddish-brown and green minerals, trace iron oxides.	Mostly disseminated opaques, a few very faint laminae.
	TR03B	2.2-2.5	Fox Hills Sandstone, very fine to medium grained, subround to subangular, very friable, light gray, 55% quartz, trace potassium feldspar/plagioclase, trace fines (<10%), 20% disseminated black opaque minerals, abundant (12 or so in a 10 cm hand sample) 1 to <3 millimeter dark parallel bands (most are 1 mm or less), trace light reddish-brown mineral, magnetic minerals.	Visible gray to black laminae.
	TR03C	2.8-3.2	Fox Hills Sandstone, very fine to medium grained, subround to subangular, very friable, light gray, 55% quartz, trace potassium feldspar/plagioclase, trace fines (<10%), 20 to 25% disseminated black opaque minerals, few 1 to <1 millimeter dark parallel laminae (3 or 4 in a 10 cm hand sample), trace light reddish-brown mineral, magnetic minerals.	A few very light gray laminae.
TR-04	TR04A	1.1-1.4	Fox Hills Sandstone, very fine to medium grained, subround to subangular, very friable, gray, 55% quartz, trace potassium feldspar/plagioclase, trace fines (<10%), 25% disseminated black/dark red opaque minerals, abundant (11 or so in 10 cm hand sample) black to gray parallel laminae (<1 to 2 mm thick) containing opaques and reddish brown minerals, some darker bands are separated by different wider bands of varying gray color with variations of mineral abundances (sometimes up to 1-2 cm thick) opaque and reddish-brown minerals, magnetic minerals.	Visible gray to black laminae.
	TR04B	1.8-2.1	Fox Hills Sandstone, very fine to medium grained, subround to subangular, very friable, gray, 60% quartz, trace potassium feldspar/plagioclase, trace fines, 20-25% disseminated black opaques/reddish-brown minerals, abundant (8 or 9 in a 7.5 cm hand sample) dark gray to black parallel bands (some reddish-brown minerals also) <1 to 1 millimeter thick, magnetic minerals.	Visible gray to black laminae.
	TR04C	2.9-3.2	Fox Hills Sandstone, very fine to medium grained, subround to subangular, very friable, gray, 55% quartz, trace potassium feldspar/plagioclase, trace fines, 20-25% disseminated black opaque/reddish-brown minerals, trace green mineral, abundant (8 or 9 in 7.5 cm hand sample) darker parallel bands <1 millimeter thick, magnetic minerals.	Visible gray to black laminae.
TR-05	TR05A	1.2-1.9	Fox HIlls Sandstone, fine to medium grained, subround to subangular, very friable, light gray, 60% quartz, trace potassium feldspar/plagioclase, trace fines, few darker <1 to 1 mm thick parallel bands (4 or 5 at bottom of 20 cm sample), trace light pink mineral, trace iron oxides, 15-20% disseminated opaque black and some reddish-brown minerals, magnetic minerals.	Mostly disseminated opaque minerals, few gray laminae.
	TR05B	2.4-2.8	Fox Hills Sandstone, very fine to medium grained, subround to subangular, extremely friable, gray to dark gray, 50% quartz, trace fines, 35%+ opaque and pink and green minerals, abundant gray to black parallel bands (hard to see how many because hand sample disaggregated), trace iron oxide, magnetic minerals.	Visible gray to black laminae.
	TR05C	3-3.3	Fox Hills Sandstone, very fine to medium grained, subround to subangular, extremely friable, gray to dark gray, rip-up clasts (black to dark gray), abundant dark gray bands (hard to see how many because hand sample disaggregated), trace iron oxide, 50% quartz, 30% opaque and reddish brown mineral, trace pink mineral, trace potassium feldspar/plagioclase, magnetic minerals.	Visible gray to black laminae.
TR-06	TR06A	3.6-4.2	Fox Hills Sandstone, very fine to medium grained, subround to subangular, very friable, gray to light gray, few dark gray to black parallel bands 1 to <1 millimeters thick (opaques and reddish-brown to pink mineral) near the bottom, 55% quartz, trace potassium feldspar/plagioclase, trace fines, trace iron oxide.	Mostly disseminated opaque minerals, few visible dark gray to black laminae.
	TR06B	4.3-4.6	Fox Hills Sandstone, very fine to medium grained, subround to subangular, very friable, gray to dark gray, abundant dark gray to black parallel bands (10 or so in a 10 cm hand sample, <1 to 1.5 mm thick), 50% quartz, 35% black opaques and reddish to pinkish brown mineral, magnetic minerals, trace potassium feldspar/plagioclase, trace fines, trace iron oxide.	Visible dark gray to black laminae.
	TR06C	4.9-5.4	Fox Hills Sandstone, very fine to medium grained, subround to subangular, very friable, gray to dark gray, black to gray parallel bands (2 or 3, < 1 mm), 55% quartz, trace potassium feldspar/plagioclase, trace iron oxide, 25 to 30% opaques and reddish-brown/pinkish minerals, trace fines.	Visible black to gray laminae.

Notes: Descriptions for samples sent for XRF, ICP-MS, and automated mineralogy only. [1] Sample interval is feet below lowest indurated sandstone.

and titanite (a.k.a. sphene) at average concentrations of 7.7, 2.8, and 2.3 vol. %, respectively. Other minerals detected in the samples with abundant heavy-mineral laminae include garnet (average = 7.3 vol. %), epidote (3.2%) and zircon (1.8%). Previous studies indicate that most of the garnet is almandine ($Fe^{2+}{}_3Al_2Si_3O_{12}$) (WGM, 2000). Other garnet types may be present. Analyses of some of the thin sections was performed using a petrographic microscope to verify the garnet/epi-

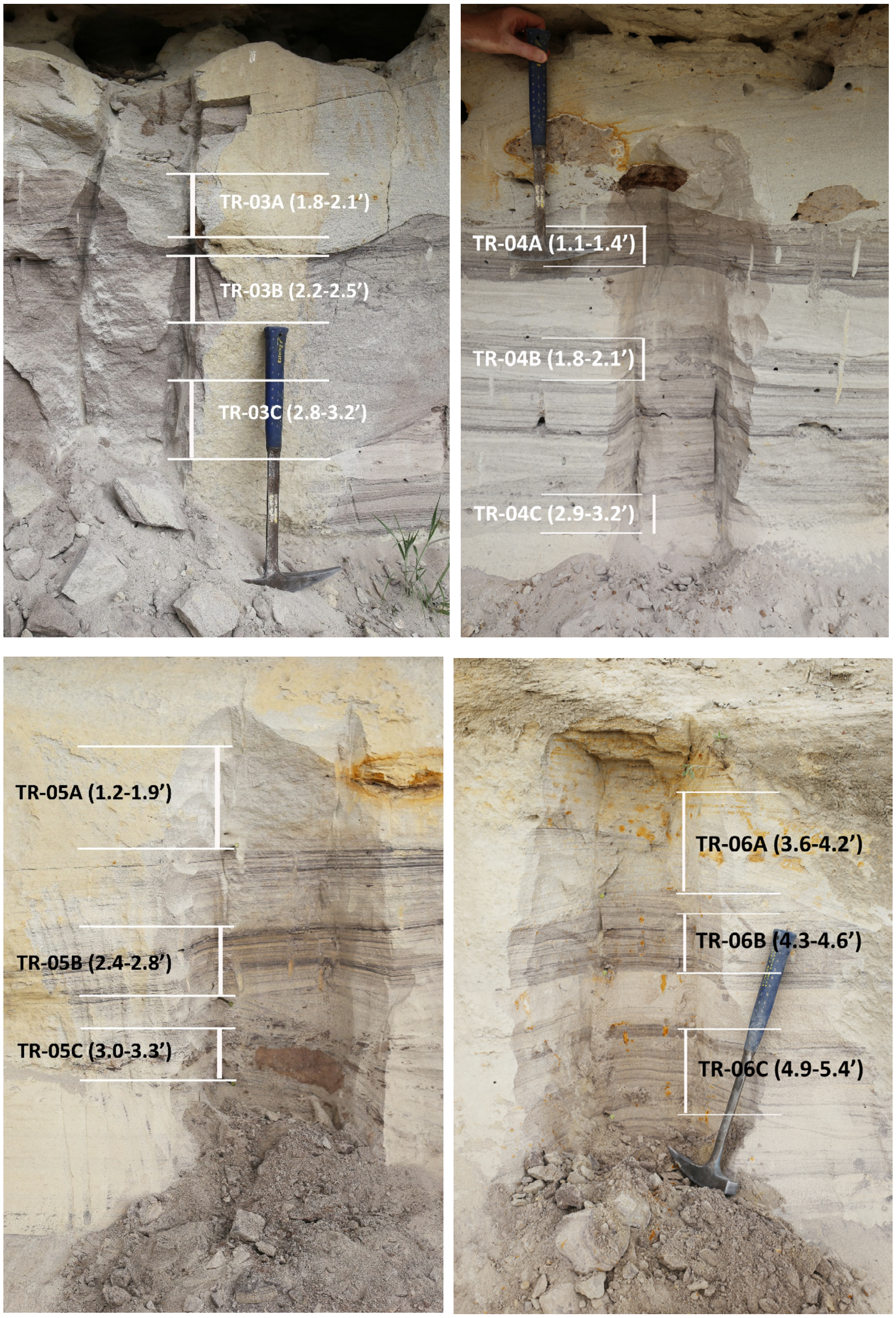


Figure 22. *Annotated outcrop photos showing sample intervals in the Fox Hills Sandstone, Titanium Ridge area, Colorado. TR-03 (top left), TR-04 (top right), TR-05 (bottom left), and TR-06 (bottom right). Hammer is ~40.6 cm (16 inches) long. Sample interval is in feet below an overlying indurated sandstone bed.*

dote mineralogy. During this analysis, minerals initially categorized as garnet Ca-Fe or epidote (clinozoisite) during the automated mineralogy analysis were determined to be epidote based on petrographic analysis. These values were updated in Table 10 to reflect this change. **Figures 33 and 34** show photos of select minerals in thin section relative to the automated mineralogy analysis.

Analyses of the samples containing abundant heavy-mineral laminae by automated mineralogy detected the REE-bearing minerals allanite (Ce), monazite, and xenotime at average concentrations (in 9 samples) of 0.71, 0.11, and 0.02 vol. %, respectively. The presence of allanite was verified in thin section by its optical properties (**Figure 35**). It is unclear if these are the only minerals contributing to the detected ICP-MS REE concentrations, or if higher concentrations of monazite are present in the finer grain-size fraction that may not have been completely quantified by automated mineralogy. Analysis of composite samples collected along the western beach placer trend (Figure 15) detected 3.2 wt. % of allanite and 0.9 wt. % of monazite within the heavy mineral suite (WGM, 2000). Monazite was reported by Pirkle and others (2012) at concentrations up to 0.3% of the heavy mineral suite—when present, the monazite was reportedly fine grained and in the 140 mesh sieve size (0.106 mm). Other detected minerals include: muscovite, tourmaline (schorl and dravite), apatite, chromite, corundum, and biotite (Table 10). Sandstone samples collected above the heavy-mineral laminae, in areas with disseminated heavy minerals, generally contained these minerals at lower, by about an order of magnitude, concentrations with increased quartz, plagioclase, and orthoclase content (Table 10).

Automated mineralogy analysis was also conducted on smaller areas within each thin section and in some cases, focused on areas with heavy-mineral laminae. As shown in Figures 24 through 27 and summarized in Table 11, most of the heavy minerals are concentrated in areas containing generally parallel sub-centimeter laminae within the Fox Hills Sandstone. For example, a lamina in sample TR-04A contains over 50 vol. % heavy minerals with 34 vol. % titanium minerals (ilmenite = 23.75%, rutile = 4.12%, and titanite = 6.39%), 18% garnet, 5.4% zircon, 4.95% epidote, and 1.8% allanite (Figure 25, Table 11). The interval between these laminae contains elevated concentrations of the same minerals (Figures 24 through 27). Also, analysis of the minerals in the rip-up clasts observed at location TR-05C determined that they are typically composed of older beach-placer fragments as shown in Figure 26b.

During the petrographic analysis of the Fox Hills Sandstone thin sections, the CGS observed highly fractured quartz

Table 8. *Summary of Fox Hills Sandstone XRF laboratory analysis results.*

		Normalized Major Elements (Weight %)									
Sample	**HM Description**	**SiO_2**	**TiO_2**	**Al_2O_3**	**FeO***	**MnO**	**MgO**	**CaO**	**Na_2O**	**K_2O**	**P_2O_5**
TR03A	disseminated	84.62	1.45	8.24	1.87	0.11	0.28	0.52	0.61	2.27	0.04
TR03B	laminae	64.08	11.43	7.73	10.77	0.76	0.81	3.26	0.50	0.51	0.16
TR03B®	laminae	64.24	11.48	7.72	10.81	0.76	0.84	3.27	0.19	0.53	0.16
TR03C	laminae	68.80	9.62	7.34	9.11	0.62	0.71	2.88	0.19	0.61	0.13
TR04A	laminae	64.05	10.99	8.26	10.48	0.74	0.85	3.83	0.15	0.49	0.16
TR04B	laminae	71.91	8.08	7.15	7.87	0.54	0.64	2.61	0.25	0.82	0.14
TR04C	laminae	70.02	8.38	7.84	8.22	0.55	0.69	3.27	0.18	0.64	0.21
TR05A	few laminae	85.80	1.53	7.26	1.83	0.11	0.26	0.39	0.66	2.12	0.04
TR05B	laminae	66.60	10.65	7.50	10.25	0.67	0.72	1.91	0.44	1.07	0.18
TR05C	laminae	71.38	8.80	6.81	8.78	0.53	0.56	1.34	0.45	1.18	0.17
TR06A	few laminae	84.29	2.22	7.23	2.63	0.17	0.31	0.74	0.50	1.85	0.05
TR06B	laminae	63.44	11.52	7.77	11.33	0.76	0.75	3.22	0.23	0.59	0.38
TR06C	laminae	65.17	10.82	7.83	10.53	0.69	0.81	3.33	0.15	0.45	0.23
Trace Elements (parts per million)											
		NiO	**Cr_2O_3**	**Sc_2O_3**	**V_2O_3**	**BaO**	**Rb_2O**	**SrO**	**ZrO_2**	**Y_2O_3**	**Nb_2O_5**
TR03A	disseminated	7.29	74.77	1.85	74.66	629.38	72.17	96.03	2917.25	68.92	56.93
TR03B	laminae	19.27	468.19	60.51	289.87	449.76	15.91	159.57	33969.74	485.68	463.55
TR03B®	laminae	19.92	464.27	61.30	305.32	480.12	14.80	158.84	34425.95	489.21	466.79
TR03C	laminae	16.78	395.02	41.71	263.50	478.51	17.89	144.10	25529.69	414.13	395.77
TR04A	laminae	18.22	418.06	61.14	293.51	458.96	15.57	178.81	25240.43	472.21	458.98
TR04B	laminae	16.48	330.51	45.68	230.78	488.67	25.37	141.98	19470.61	360.37	332.40
TR04C	laminae	17.65	328.87	49.44	249.69	458.38	19.79	167.79	18149.01	382.52	349.18
TR05A	few laminae	7.16	87.99	8.17	66.09	634.42	69.26	100.31	4389.65	76.20	56.36
TR05B	laminae	23.33	493.03	47.40	282.29	688.85	31.04	128.02	43244.45	450.10	416.69
TR05C	laminae	22.68	434.46	41.55	247.59	674.70	34.57	133.62	39733.58	365.34	336.54
TR06A	few laminae	9.82	112.89	9.03	77.05	525.71	60.06	113.91	5588.45	112.92	87.99
TR06B	laminae	20.71	482.04	53.72	292.60	484.49	16.57	176.74	38268.51	485.81	456.77
TR06C	laminae	22.02	435.97	56.40	291.99	513.82	13.36	176.50	29361.95	454.15	442.04
Trace Elements (parts per million)											
		Ga_2O_3	**CuO**	**ZnO**	**PbO**	**La_2O_3**	**CeO_2**	**ThO_2**	**Nd_2O_3**	**U_2O_3**	
TR03A	disseminated	11.62	4.03	27.27	17.21	169.49	323.55	30.39	104.91	5.97	
TR03B	laminae	3.60	8.25	113.47	54.37	1071.70	1992.51	240.26	815.98	48.19	
TR03B®	laminae	5.26	6.19	114.62	54.37	1108.42	2007.70	245.15	813.33	45.47	
TR03C	laminae	6.51	6.96	94.49	46.71	907.66	1698.01	188.89	664.24	32.77	
TR04A	laminae	8.03	6.83	104.75	46.38	1092.48	1958.20	210.71	790.15	38.55	
TR04B	laminae	6.86	5.87	81.26	37.47	794.06	1468.12	156.33	561.55	30.09	
TR04C	laminae	9.05	5.75	85.70	38.02	812.00	1507.61	161.06	582.37	28.30	
TR05A	few laminae	10.27	4.03	23.52	17.00	160.06	305.27	40.14	104.91	7.30	
TR05B	laminae	0.28	7.35	107.82	54.15	1053.10	1951.11	277.20	795.67	48.87	
TR05C	laminae	0.28	9.93	88.59	54.92	860.55	1609.13	249.92	644.78	46.37	
TR06A	few laminae	8.60	4.19	33.10	18.59	219.98	476.12	58.35	169.18	10.39	
TR06B	laminae	3.05	6.96	111.16	58.47	1079.07	2007.45	278.22	819.46	50.68	
TR06C	laminae	4.98	6.45	100.52	50.48	980.86	1814.87	223.78	724.19	40.71	

Notes: Major elements are normalized on a volatile-free basis, with total Fe expressed as FeO. These are semi-quantitative results due to the elevated concentrations of zirconium that were outside normal operating ranges and calibration. Estimated results due to interferences. ® denotes a duplicate bead made from the same rock powder. HM - Heavy-minerals.

grains in several samples including TR-03B, TR-03C, TR-04A, and TR-04B. These observations were confirmed by other researchers. The fractures in the quartz may be regularly spaced but subparallel and curvilinear or they can be conchoidal; in some cases, the quartz grains are shattered with concussion fractures at their margins. Analysis of some of these grains in thin sections did not provide any clear evidence as to their origin; however, the features observed were likely not associated with shock metamorphism (Christian Koeberl, written commun., 2020).

Table 9. *Summary of Fox Hills Sandstone ICP-MS laboratory analysis results.*

						Lanthanides														
						LREE (ppm)							HREE (ppm)							
Sample Location	HM Description	Interval*	Total REE	Total LREE	Total HREE	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y
TR-03A	disseminated	1.8 - 2.1	637	556	81	147.1	262.8	27.8	92.0	14.0	1.7	10.2	1.5	9.7	2.1	6.0	1.0	6.6	1.1	53.2
TR-03B	laminae	2.2 - 2.5	4,909	4,205	704	1,041.7	2,052.5	208.3	697.0	111.2	11.9	82.1	13.1	82.6	17.7	52.4	8.5	59.4	9.8	461.0
TR-03C	laminae	2.8 - 3.2	3,838	3,283	556	811.5	1,603.3	162.2	545.0	86.9	9.6	64.2	10.3	65.0	13.9	41.8	6.7	46.7	7.7	363.6
TR-04A	laminae	1.1 - 1.4	4,591	3,950	641	978.1	1,933.8	194.8	652.8	103.3	12.0	75.1	12.1	76.1	16.1	48.0	7.6	52.3	8.6	420.3
TR-04B	laminae	1.8 - 2.1	3,302	2,820	482	720.6	1,338.8	143.9	477.6	75.2	8.7	55.2	8.8	56.2	12.1	36.1	5.7	39.7	6.5	316.8
TR-04C	laminae	2.9 - 3.2	3,760	3,219	541	790.5	1,572.0	159.4	537.6	85.7	10.2	63.2	10.2	64.2	13.7	41.0	6.3	43.9	7.2	354.6
TR-05A	few laminae	1.2 - 1.9	661	568	94	144.7	267.0	28.9	98.0	16.2	1.6	11.5	1.8	11.1	2.4	7.1	1.1	8.0	1.4	60.8
TR-05B	laminae	2.4 - 2.8	4,658	4,003	655	978.2	1,961.7	197.6	669.1	107.5	9.7	79.5	12.4	75.9	16.4	49.7	7.9	57.0	9.6	425.9
TR-05C	laminae	3.0 - 3.3	3,696	3,193	503	774.3	1,558.8	158.6	540.6	88.8	6.9	64.8	9.9	59.5	12.5	37.8	6.1	43.6	7.4	326.1
TR-06A	few laminae	3.6 - 4.2	933	798	135	203.2	376.4	40.7	136.4	22.2	2.5	16.9	2.6	16.2	3.4	10.0	1.6	11.2	1.8	88.0
TR-06B	laminae	4.3 - 4.6	4,685	4,004	681	977.1	1,966.1	196.9	665.2	107.8	11.0	79.7	12.7	78.5	17.1	51.2	8.3	57.5	9.6	446.3
TR-06C	laminae	4.9 - 5.4	4,243	3,628	614	887.3	1,782.1	179.3	600.8	96.0	10.8	72.0	11.5	71.9	15.6	45.8	7.3	50.7	8.4	403.2
Average (all samples)			3,326	2,852	474	704.5	1,389.6	141.5	476.0	76.2	8.0	56.2	8.9	55.6	11.9	35.6	5.7	39.7	6.6	310.0
Upper Crustal Abundance						30.0	64.0	7.1	26.0	4.5	0.9	3.8	0.6	3.5	0.8	2.3	0.3	2.2	0.3	22.0

			Other Elements (ppm)											
Sample Location	HM Description	Interval*	Sc	Nb	Ta	Th	U	Ba	Zr	Hf	Pb	Rb	Sr	Cs
TR-03A	disseminated	1.8 - 2.1	4.9	36.8	3.0	28.3	5.8	572.5	1,908.8	48.2	15.6	64.5	74.0	1.5
TR-03B	laminae	2.2 - 2.5	32.8	316.5	26.8	228.9	49.0	450.7	19,969.6	473.4	50.8	17.5	143.2	0.5
TR-03C	laminae	2.8 - 3.2	27.1	254.9	21.9	171.5	36.9	416.2	14,009.2	351.4	40.5	19.1	124.0	0.5
TR-04A	laminae	1.1 - 1.4	32.4	304.3	26.3	192.0	40.0	390.3	14,145.4	356.5	43.8	16.2	157.4	0.6
TR-04B	laminae	1.8 - 2.1	24.3	221.3	18.9	145.3	30.9	435.9	11,305.6	283.5	35.4	25.4	123.4	0.8
TR-04C	laminae	2.9 - 3.2	27.7	248.4	21.6	160.1	33.3	431.3	11,496.7	290.9	37.5	22.0	155.2	0.6
TR-05A	few laminae	1.2 - 1.9	3.9	37.2	3.1	37.7	7.9	595.3	2,935.3	74.1	16.0	63.3	79.3	1.4
TR-05B	laminae	2.4 - 2.8	26.2	270.2	23.0	252.5	52.4	631.6	22,669.0	538.3	50.9	32.6	121.8	0.8
TR-05C	laminae	3.0 - 3.3	18.2	206.3	17.4	216.4	42.9	601.3	18,055.3	429.8	49.2	34.8	116.6	0.8
TR-06A	few laminae	3.6 - 4.2	6.3	56.1	4.8	53.1	9.9	488.7	3,397.3	85.4	16.9	54.1	88.2	1.4
TR-06B	laminae	4.3 - 4.6	29.3	291.3	24.8	247.9	50.1	419.4	20,727.9	486.6	51.7	18.7	161.8	0.5
TR-06C	laminae	4.9 - 5.4	30.8	286.7	24.4	200.4	41.2	449.9	16,093.7	377.8	44.9	14.9	153.1	0.5
Average (all samples)			22.0	210.8	18.0	161.2	33.3	490.3	13,059.5	316.3	37.8	31.9	124.8	0.8
Upper Crustal Abundance			11.0	25.0	2.2	10.7	2.8	550.0	190.0	5.8	20.0	112.0	350.0	3.7

HM - heavy minerals
HREE - heavy rare earth elements (Tb, Dy, Ho, Er, Tm, Yb, Lu, Y)
ICP-MS - inductively coupled plasma mass spectrometry
LREE - light rare earth elements (La, Ce, Pr, Nd, Sm, Eu, Gd)
LREE and HREE designations are based on Van Gosen and others (2014b and 2017) - other studies may define these categories differently.

Notes: All results in parts per million (ppm) by inductively coupled plasma mass spectroscopy (ICP-MS) analysis.
These are semi-quantitative results due to the elevated concentrations of zirconium that were outside normal operating ranges and calibration.
REE concentrations are likely within 10%. Upper crustal abundance from Taylor and McClennan, 1985.
** feet below top of first indurated sandstone at the surface.*

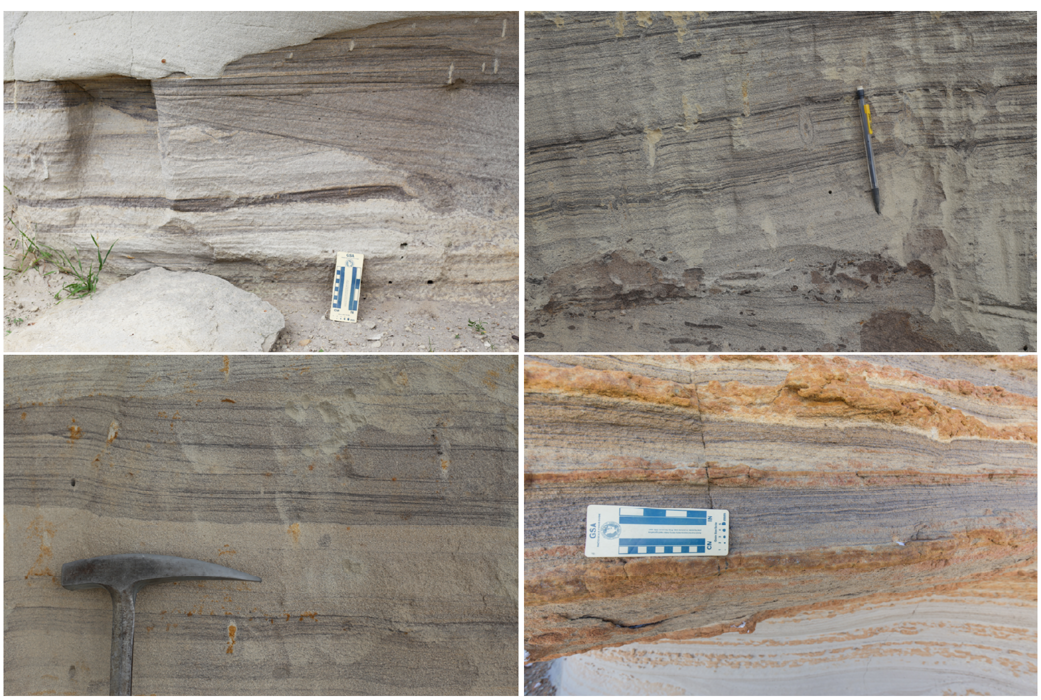


Figure 23. *Close-up photos of heavy-mineral laminae in the Fox Hills Sandstone, Titanium Ridge area, Colorado. From top left to lower right – near TR-03, at TR-05, at TR-06, and on the top of Titanium Ridge near TR-13. Scale card is ~16.5 cm (~6.5 inches) long. Hammer head is ~18.5 cm (~7.0 inches).*

Table 10. *Summary of Fox Hills Sandstone thin section automated-mineralogy results.*

Mineral	Sample	TR03A	TR03B	TR03C	TR04A	TR04B	TR04C	TR05A	TR05B	TR05C	TR06A	TR06B	TR06C		
	General Formula - HM Sample Description	HM poor, disseminated HM	HM laminations	HM laminations	HM laminations	HM laminations	HM laminations	HM poor, few HM laminae	HM laminations	HM laminations + rip-up clasts	HM poor, few HM laminae	HM laminations	HM laminations	Average - HM Poor, few HM laminae (Disseminated)	Average - HM Rich (Laminae)
Quartz	SiO_2	69.09	59.86	64.11	49.46	55.91	60.51	68.6	52.6	59	67.55	57.97	57.25	68.41	57.41
Plagioclase	$NaAlSi_3O_8$ - $CaAl_2Si_2O_8$	6.57	3.31	2.62	2.21	2.85	3.13	7.11	4.45	4.87	6.52	2.74	2.5	6.73	3.19
Orthoclase	$K(AlSi_3O_8)$	9.27	2.27	2.62	1.4	2.44	2.45	8.11	4.62	5.56	7.12	1.76	1.74	8.17	2.76
Aluminosilicates	$Al_2O_3 + SiO_2$	6.81	3.01	3.24	2.84	3.02	3.56	5.7	3.65	6.35	5.05	2.8	3.41	5.85	3.54
Carbonates	$(CO_3)^{2-}$	0.06	0.44	0.48	0.91	0.74	0.73	0.06	0.35	0.2	0.17	0.6	0.66	0.10	0.57
Iron Oxides	-	0.09	0.87	0.74	0.94	0.88	0.85	0.16	0.87	0.6	0.31	0.96	0.83	0.19	0.84
Garnet (Fe-Ca)	$(Fe, Ca)\ Al_2Si_3O_{12}$	0.86	6.3	6.19	11.26	8.15	6.47	1.34	7.44	4.0	2.38	7.54	8.47	1.53	7.31
Epidote	$Ca_2(Al, Fe)Al_2O(SiO_4)(Si_2O_7)(OH)$	0.27	3.16	2.74	4.95	3.6	3.67	0.43	2.05	1.12	0.99	3.62	3.89	0.56	3.20
Ilmenite	$FeTiO_3$	0.83	7.63	5.91	9.26	7.88	6.18	1.75	9.92	7.54	2.69	7.87	7.33	1.76	7.72
Rutile	TiO_2	0.29	2.84	2.49	3.96	3.06	2.44	0.59	2.79	1.7	0.86	3.05	3.23	0.58	2.84
Titanite (sphene)	$CaTiO(SiO_4)$	0.2	1.99	2.15	3.74	2.74	2.3	0.26	1.71	0.76	0.66	2.56	2.74	0.37	2.30
Zircon	$(Zr,Hf,U)SiO_4$	0.18	1.89	1.36	1.87	1.61	1.19	0.43	2.49	2.18	0.72	2.06	1.55	0.44	1.80
Allanite (Ce)	$(Ca,Ce)_3(Fe^{2+},Fe^{3+})Al_2O(SiO_4)(Si_2O_7)(OH)$	0.08	0.74	0.57	1.04	0.87	0.65	0.13	0.76	0.37	0.25	0.7	0.7	0.15	0.71
Monazite	$(Ce,La,Y,Th)PO_4$	0.01	0.12	0.08	0.11	0.11	0.08	0.03	0.16	0.17	0.05	0.1	0.1	0.03	0.11
Xenotime	YPO_4	-	0.02	0.01	0.03	0.02	0.01	0.01	0.02	0.03	0.01	0.03	0.02	0.01	0.02
Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$	1.93	1.07	1.1	0.87	1.12	0.98	1.72	1.2	1.45	1.49	1.03	0.86	1.71	1.08
Schorl (tourmaline)	$(Na,Ca)(Li,Mg,Al)(Al,Fe,Mn)_6(BO_3)_3(Si_6O_{18})(OH)_4$	0.08	0.3	0.31	0.47	0.32	0.35	0.08	0.23	0.15	0.14	0.43	0.35	0.10	0.32
Dravite (tourmaline)	$(Na,Ca)(Li,Mg,Al)(Al,Fe,Mn)_6(BO_3)_3(Si_6O_{18})(OH)_4$	0.09	0.14	0.14	0.27	0.2	0.2	0.06	0.15	0.11	0.13	0.19	0.2	0.09	0.18
Apatite	$Ca_5(PO_4)_3(F,Cl,OH)$	-	-	-	0.06	0.09	0.19	0.02	0.01	-	0.09	0.15	0.01	0.06	0.09
Chromite	$FeCr_2O_4$	0.01	0.03	0.01	0.05	0.02	0.03	0.01	0.05	0.02	0.01	0.04	0.04	0.01	0.03
Corundum	Al_2O_3	-	0.02	0.02	0.04	0.02	0.02	-	0.02	0.01	-	0.05	0.05	-	0.03
Biotite	$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$	0.04	-	-	-	0.01	0.01	0.03	0.01	-	0.01	-	0.03	0.03	0.02
Other Minerals	-	0.01	0.02	0.02	0.03	0.02	0.03	0.01	0.02	0.02	0.01	0.03	0.03	0.01	0.02
Unidentified Pixels	-	3.25	3.95	3.09	4.23	4.3	3.97	3.35	4.41	3.79	2.79	3.71	4.02	3.13	3.94

Notes: Epidote was originally categorized as "Garnet (Ca-Fe) or Epidote (clinozoisite)" during the automated-mineralogy analysis. Petrographic analysis indicates that this is epidote and likely clinozoisite. All results are estimated in volume percent. HM - Heavy minerals.

Table 11. *Summary of Fox Hills Sandstone thin section automated-mineralogy results - detailed scans.*

		Volume Percent									
	Sample	TR03B	TR04A	TR05A	TR05B	TR05C	TR05C	TR06A	TR06A	TR06B	TR06B
	Analysis Number	LA#2	LA#2	LA#2	LA#2	LA#2	LA#3	LA#2	LA#3	LA#2	LA#3
Mineral	General Formula - HM Sample Description	HM laminations	HM laminations	HM poor, few HM laminae	HM laminations	HM laminations + rip-up clasts	HM laminations + rip-up clasts	HM poor, few HM laminae	HM poor, few HM laminae	HM laminations	HM laminations
Quartz	SiO_2	43.34	21.98	61.5	32.25	35.5	39.56	63.11	64.65	42.15	55.18
Plagioclase	$NaAlSi_3O_8$ - $CaAl_2Si_2O_8$	2.67	1.54	7.69	3.32	2.65	3.74	5.91	4.13	2.95	1.95
Orthoclase	$K(AlSi_3O_8)$	1.76	0.41	7.68	3.17	2.68	4.58	7.94	5.87	1.6	1.44
Alumosilicates	$Al_2O_3 + SiO_2$	1.98	2.57	5.4	2.49	1.82	10.73	6.83	7.0	3.72	2.65
Carbonates	$(CO_3)^{2-}$	0.44	1.4	0.21	0.06	0.64	0.51	-	0.06	0.44	0.8
Iron Oxides	-	0.64	0.29	0.19	0.65	1.36	0.58	0.23	0.23	0.9	0.58
Garnet (Fe-Ca)	$(Fe, Ca)\ Al_2Si_3O_{12}$	11.93	18.09	3.33	13.19	10.41	6.99	1.91	3.75	10.99	8.49
Epidote[1]	$Ca_2(Al, Fe)Al_2O(SiO_4)(Si_2O_7)(OH)$	4.45	4.95	0.08	1.75	2.87	1.2	0.13	1.33	3.96	1.54
Ilmenite	$FeTiO_3$	16.3	23.75	4.95	22.72	24.31	18.02	4.66	3.25	12.69	11.78
Rutile	TiO_2	3.4	4.12	1.14	3.81	2.77	2.13	0.51	0.95	4.3	3.06
Titanite (sphene)	$CaTiO(SiO_4)$	2.46	6.39	0.19	2.34	1.82	0.58	0.26	0.61	3.66	2.93
Zircon	$(Zr,Hf,U)SiO_4$	3.56	5.4	1.09	6.97	5.98	4.83	1.87	0.52	4.12	3.32
Allanite	$(Ca,Ce)_3(Fe^{2+},Fe^{3+})Al_2O(SiO_4)(Si_2O_7)(OH)$	1.2	1.8	0.02	1.55	1.48	0.46	0.21	0.5	1.94	1.15
Monazite	$(Ce,La,Y,Th)PO_4$	0.2	0.17	0.01	0.12	0.41	0.39	0.26	-	0.12	0.28
Xenotime	YPO_4	0.1	0.17	-	0.08	0.01	-	-	-	0.18	0.12
Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$	1.41	0.82	2.45	1.16	0.88	1.55	2.94	3.08	0.95	1.19
Schorl (tourmaline)	$(Na,Ca)(Li,Mg,Al)(Al,Fe,Mn)_6(BO_3)_3(Si_6O_{18})(OH)_4$	0.06	0.05	0.04	0.11	0.44	0.03	0.02	0.03	0.29	0.12
Dravite (tourmaline)	$(Na,Ca)(Li,Mg,Al)(Al,Fe,Mn)_6(BO_3)_3(Si_6O_{18})(OH)_4$	0.18	0.8	0.03	0.01	0.22	0.02	0.08	0.19	0.01	0.17
Apatite	$Ca_5(PO_4)_3(F,Cl,OH)$	0.01	0.04	-	0.04	0.01	0.01	-	0.02	0.1	0.02
Chromite	$FeCr_2O_4$	0.07	0.14	-	0.11	0.06	-	0.09	-	-	-
Corundum	Al_2O_3	-	0.27	-	0.2	-	-	-	-	0.11	-
Biotite	$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$	-	0.01	0.01	-	-	0.01	0.01	0.01	0.01	-
Other Minerals	-	0.01	0.02	-	0.01	0.06	0.01	0.01	0.01	0.02	0.01
Unidentified Pixels	-	3.83	4.82	3.99	3.89	3.62	4.08	3.03	3.8	4.79	3.22

Notes: All results in volume percent. All results are estimates. [1]These heavy-minerals were categorized as "Garnet (Ca-Fe) or Epidote (clinozoisite)" during the automated-mineralogy analysis. Petrographic analysis indicates that this is epidote. HM - Heavy minerals. LA - Liberation analysis.

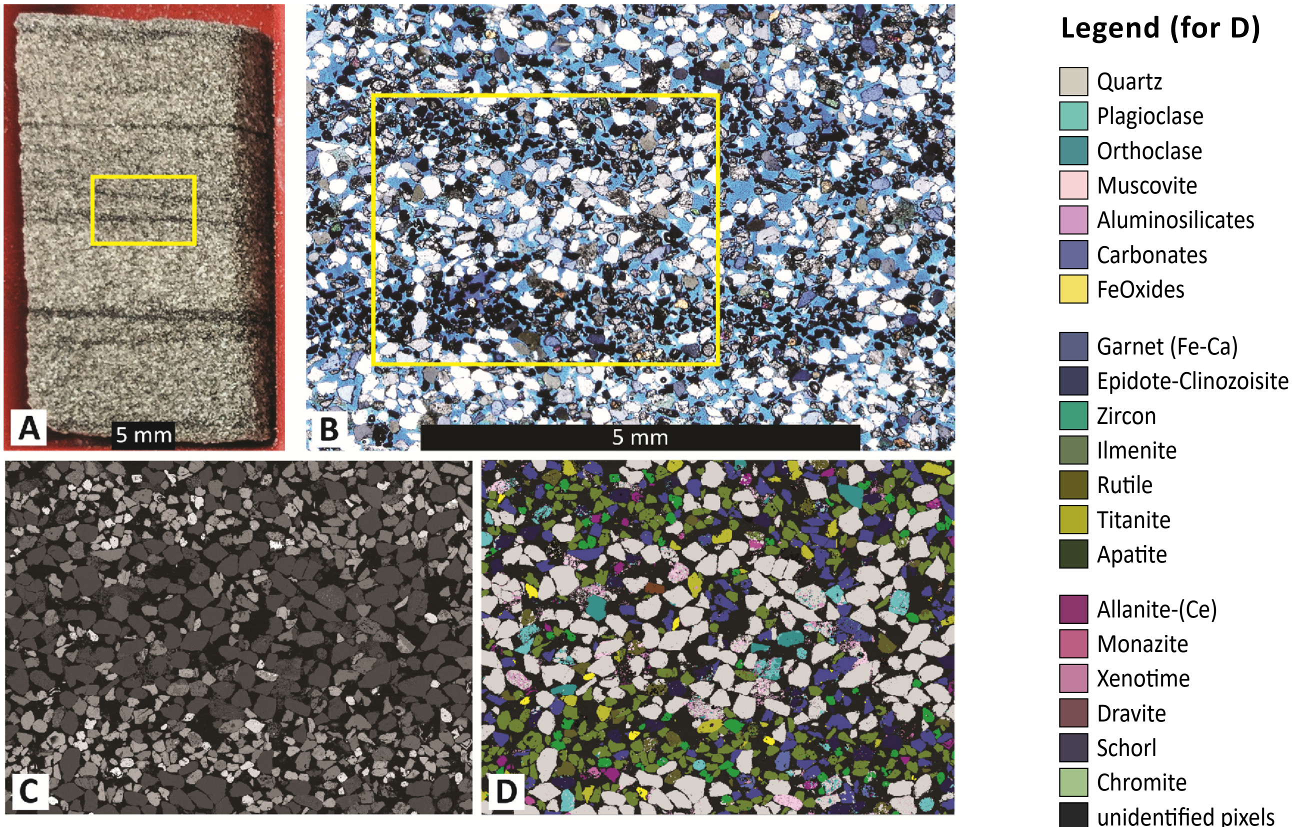


Figure 24. *TR-03B thin section and automated-mineralogy images. (A) Sample thin section billet (no epoxy); (B) Transmitted light thin section image of box shown in A; (C) Backscatter electron (BSE) image (4 mm wide) of box shown in B; (D) Automated-mineralogy image of box shown in B.*

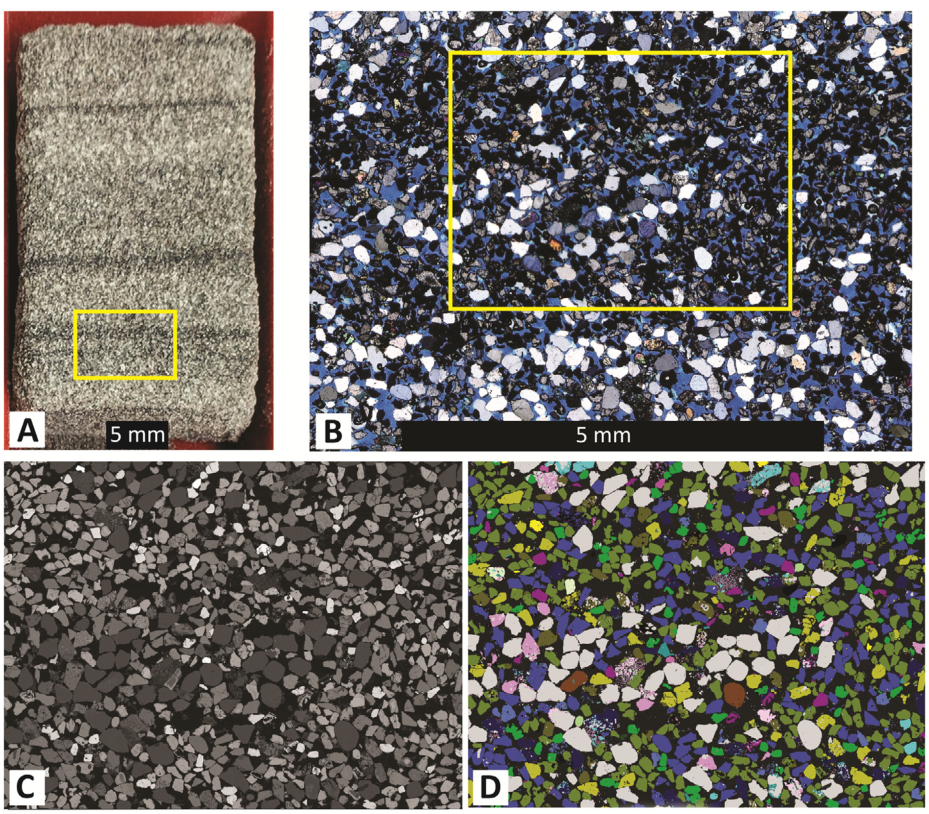


Figure 25. *TR-04A thin section and automated-mineralogy images. (A) Sample thin section billet (no epoxy); (B) Transmitted light thin section image of box shown in A; (C) Back-scatter electron (BSE) image (4 mm wide) of box shown in B; (D) Automated-mineralogy image of box shown in B.*

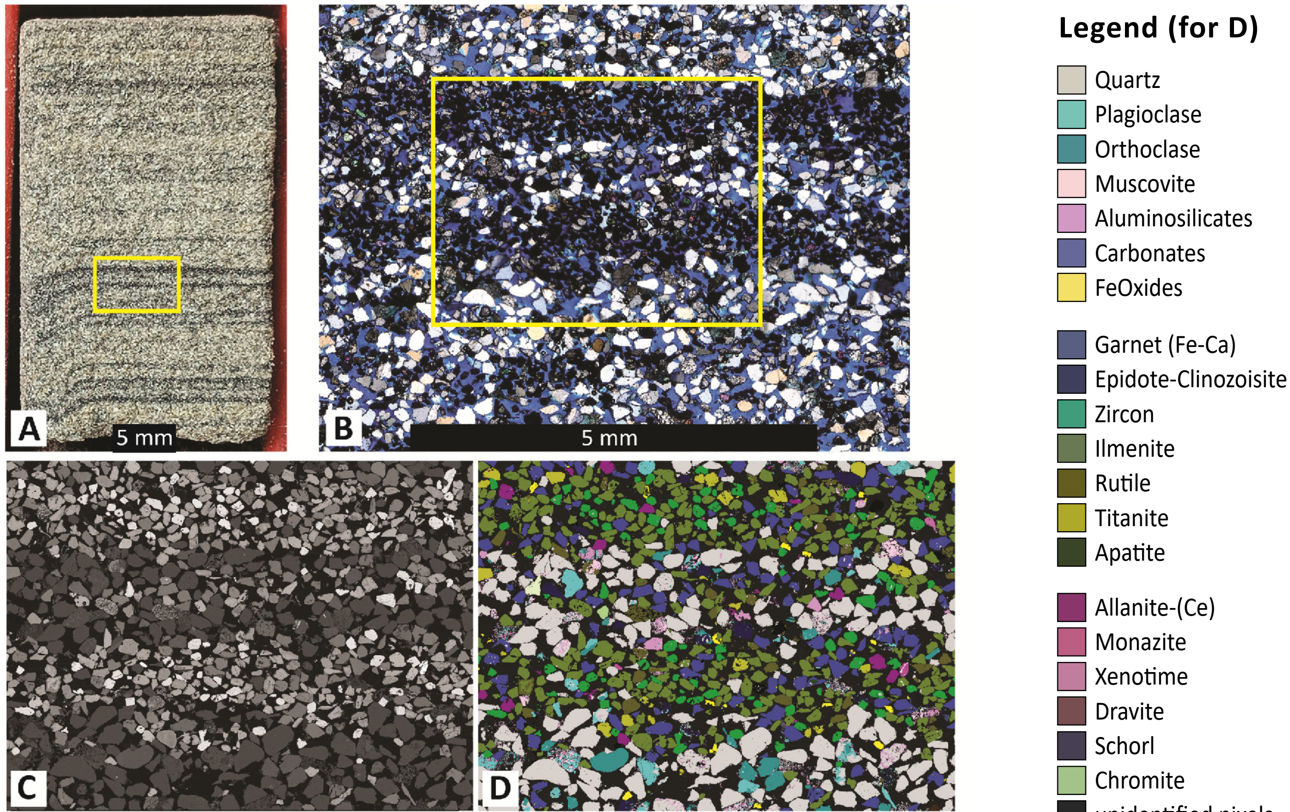


Figure 26a. *TR-05B thin section and automated-mineralogy images. (A) Sample thin section billet (no epoxy); (B) Transmitted light thin section image of box shown in A; (C) Back-scatter electron (BSE) image (4 mm wide) of box shown in B; (D) Automated-mineralogy image of box shown in B.*

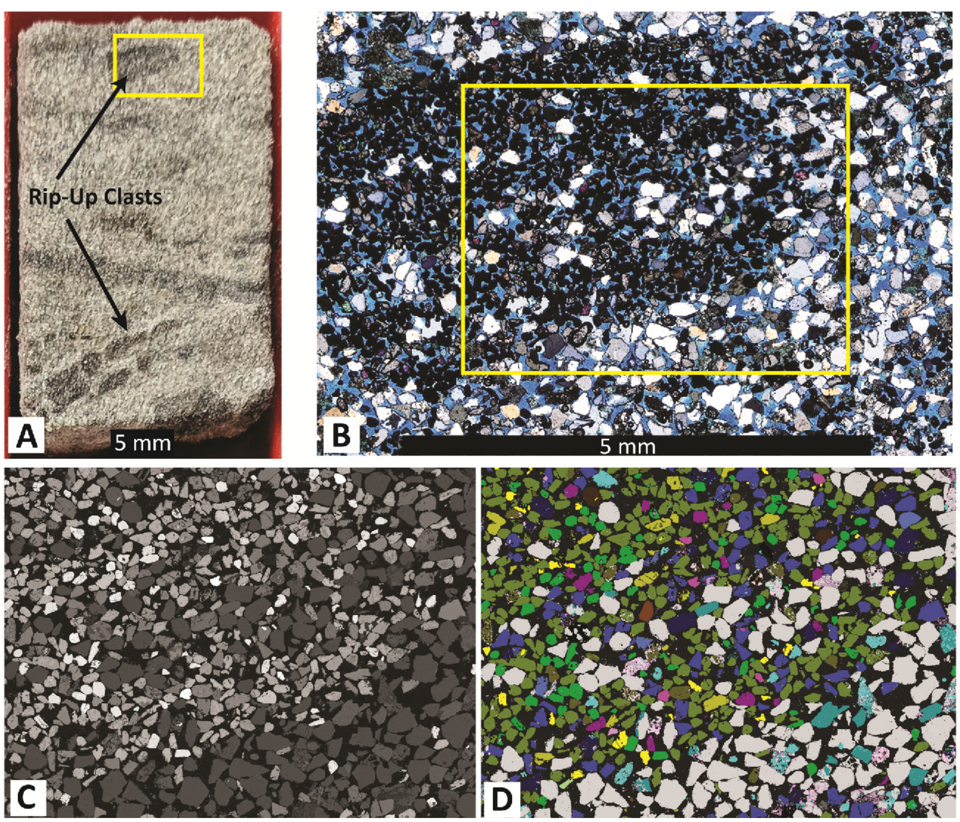


Figure 26b. *TR-05C thin section and automated-mineralogy images. (A) Sample thin section billet (no epoxy); (B) Transmitted light thin section image of box shown in A; (C) BSE image (4 mm wide) of box shown in B; (D) Automated-mineralogy image of box shown in B.*

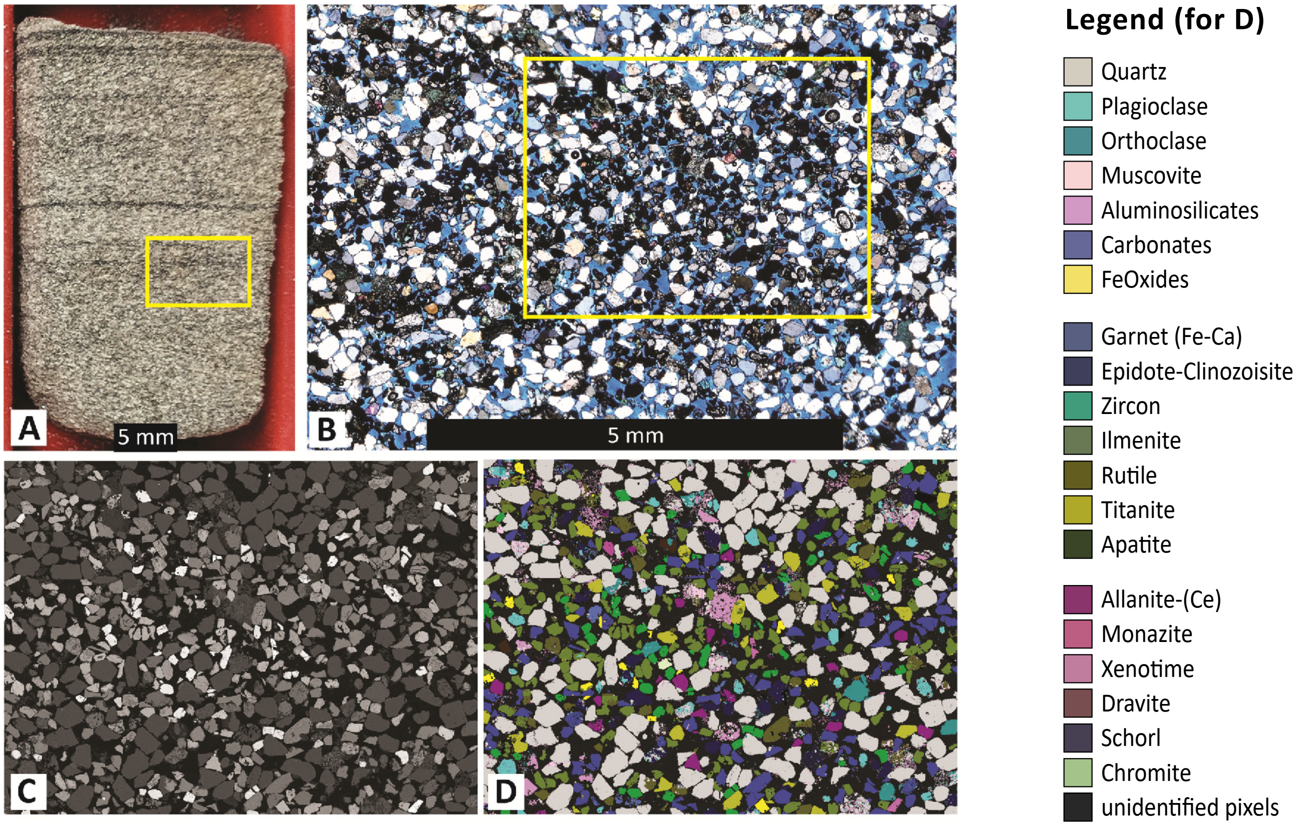


Figure 27a. *TR-06B area 1 thin section and automated-mineralogy images. (A) Sample thin section billet (no epoxy); (B) Transmitted light thin section image of box shown in A; (C) BSE image (4 mm wide) of box shown in B; (D) Automated-mineralogy image of box shown in B.*

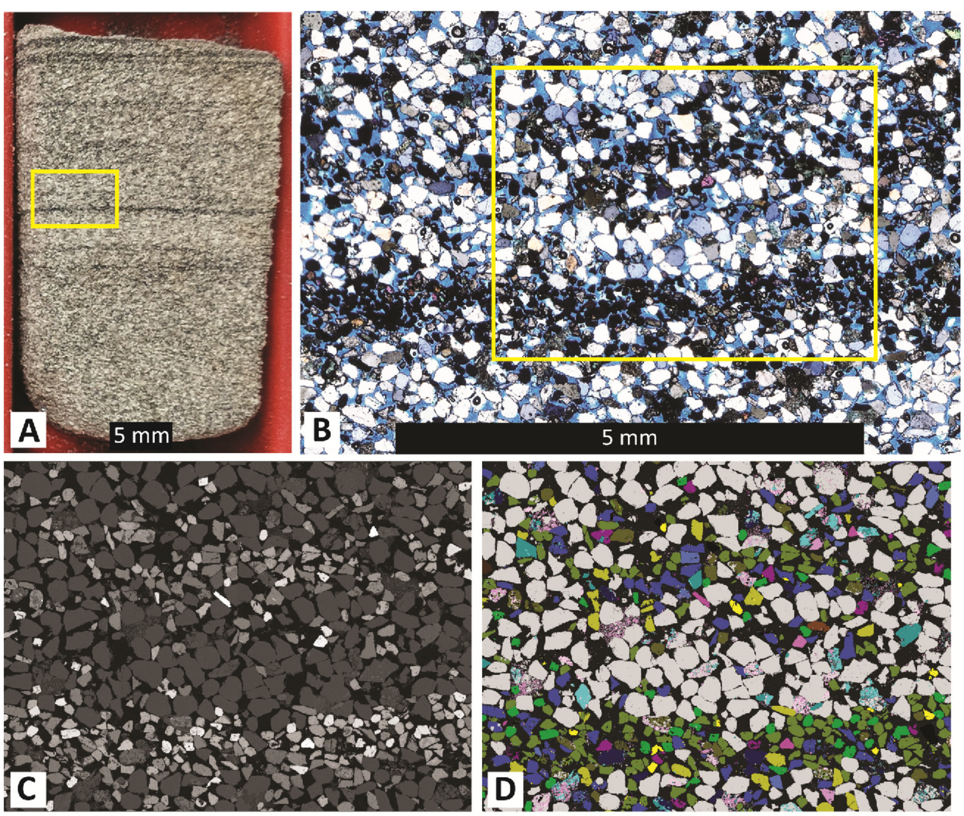


Figure 27b. *TR-06B area 2 thin section and automated-mineralogy images. (A) Sample thin section billet (no epoxy); (B) Transmitted light thin section image of box shown in A; (C) BSE image (4 mm wide) of box shown in B; (D) Automated-mineralogy image of box shown in B.*

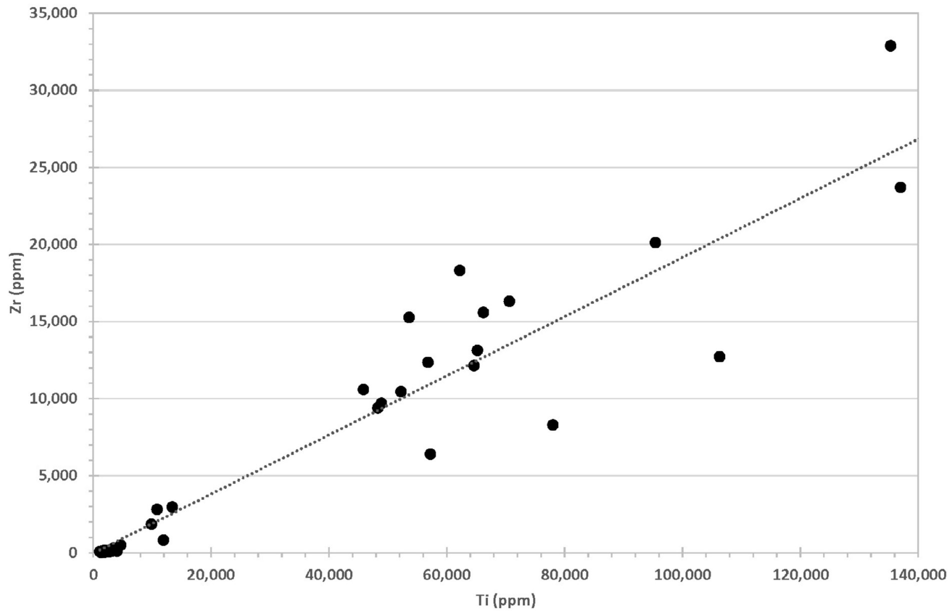


Figure 28. *Graph showing XRF field screening, zirconium versus titanium concentrations in Fox Hills Sandstone samples. Results in parts per million.*

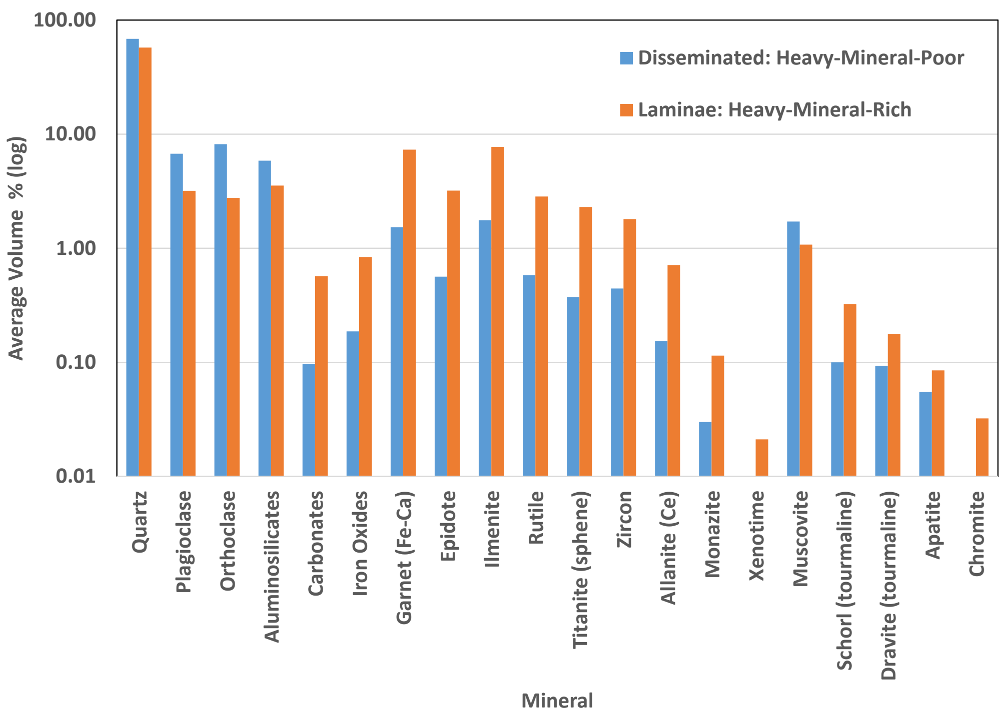


Figure 29. *Chart showing average mineral concentrations detected by automated-mineralogy analysis in heavy-mineral-rich and heavy-mineral-poor Fox Hills Sandstone samples. Results from the automated-mineralogy analysis of all samples collected from TR-03 through TR-06. Heavy-mineral-rich samples contained abundant visible heavy-mineral laminae. Heavy-mineral-poor samples were collected from beds overlying or underlying deposits with visible laminae and contained disseminated heavy minerals.*

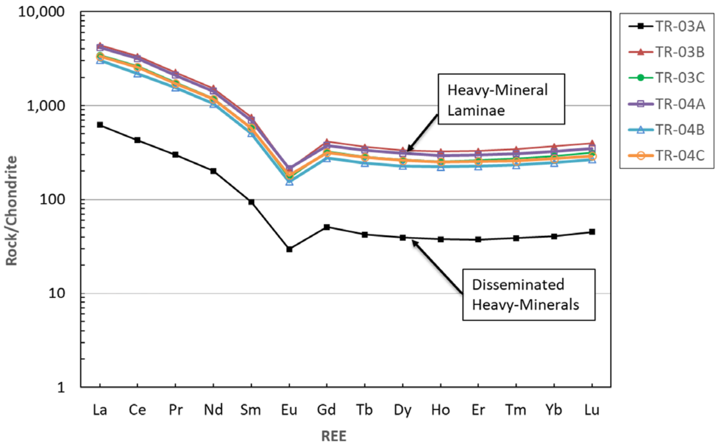


Figure 30. *Chondrite-normalized REE plot of ICP-MS results from Fox Hills Sandstone samples collected at TR-03 and TR-04. Heavy mineral-rich samples contained abundant visible heavy-mineral laminae. Heavy-mineral-poor samples were collected from beds overlying or underlying deposits with visible laminae and contained disseminated heavy minerals. Chondrite values from McDonough and Sun (1995).*

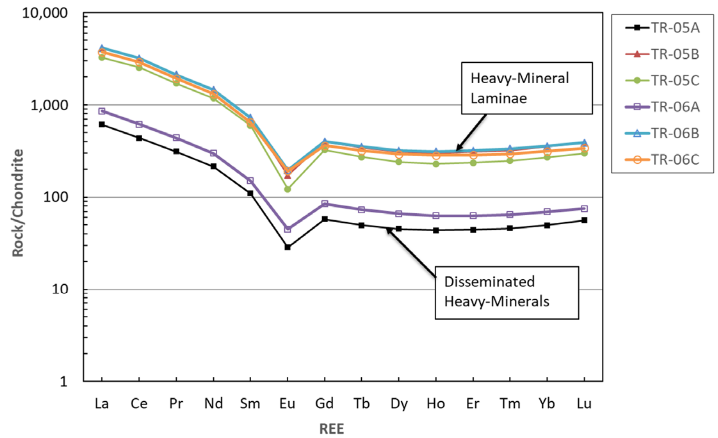


Figure 31. *Chondrite-normalized REE plot of ICP-MS results from Fox Hills Sandstone samples collected at TR-05 and TR-06. Heavy-mineral-rich samples contained abundant visible heavy-mineral laminae. Heavy-mineral-poor samples were collected from beds overlying or underlying deposits with visible laminae and contained disseminated heavy minerals. Chondrite values from McDonough and Sun (1995).*

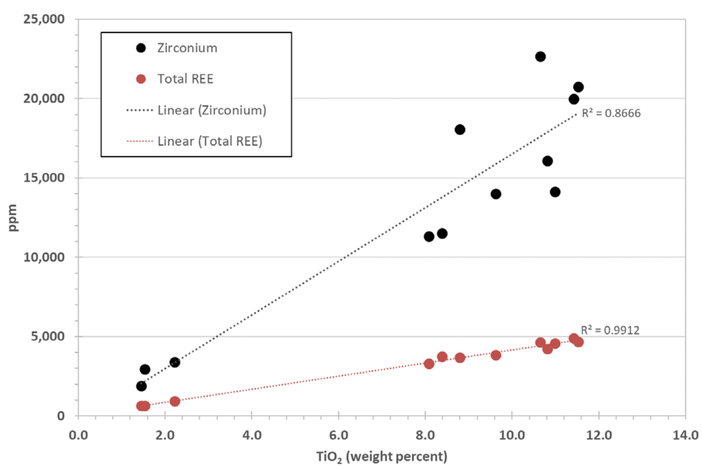


Figure 32. *Zirconium and total REE concentrations versus TiO_2 concentrations detected in Fox Hills Sandstone samples. Samples collected from TR-03 through TR-06. Zr and REE concentrations (parts per million) from laboratory ICP-MS analysis. TiO_2 from laboratory XRF analysis.*

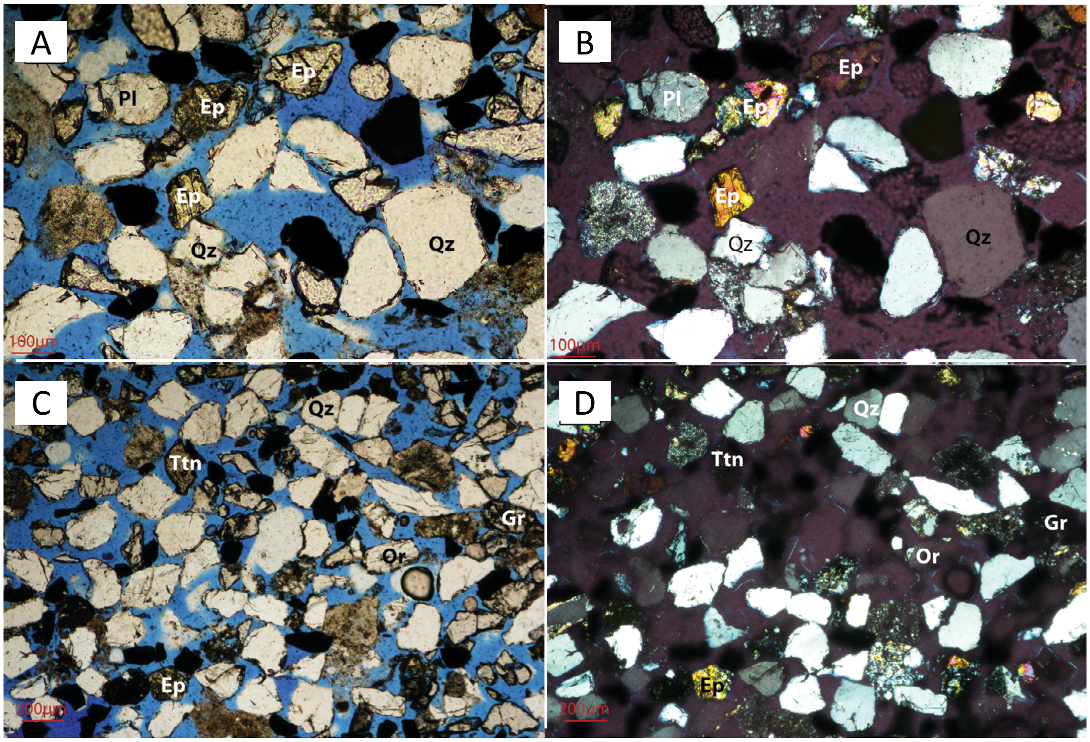


Figure 33. *Photos of select minerals in thin section, Fox Hills Sandstone sample TR-03B. (A) and (B) in transmitted light. (C) and (D) in polarized light. Ep = epidote, Gr = garnet, Or = orthoclase, Pl = plagioclase, Qz = quartz, Ttn = titanite.*

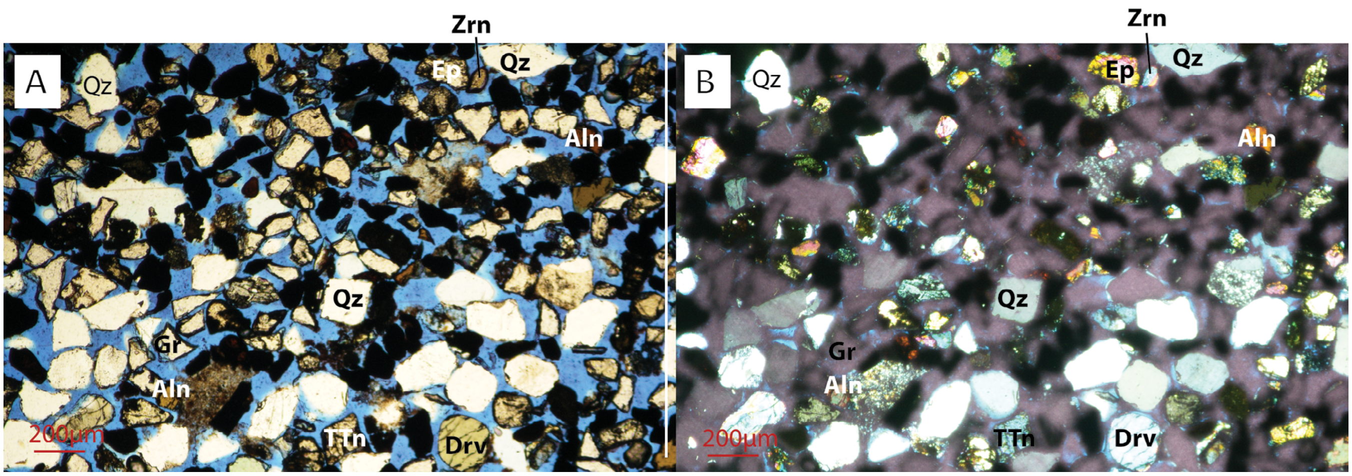


Figure 34. *Photos of select minerals in thin section, Fox Hills Sandstone sample TR-04A. (A) in transmitted light; (B) in polarized light. Aln = allanite, Drv = dravite, Ep = epidote, Grt= garnet, Qz = quartz, Ttn = titanite, Zrn = zircon.*

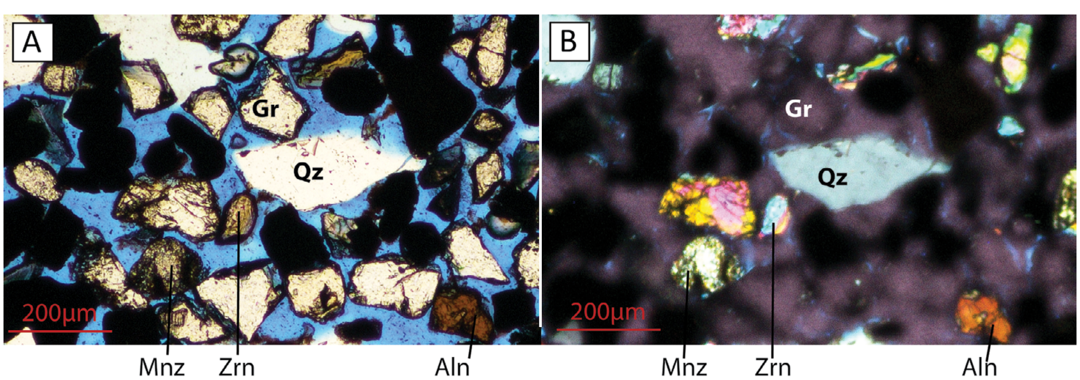


Figure 35. *Close up photos of select minerals in thin section, Fox Hills Sandstone sample TR-04A. (A) in transmitted light; (B) in polarized light. Aln = allanite, Grt= garnet, Mnz = monazite, Qz = quartz, Zrn = zircon.*

DISCUSSION

The following subsections present a discussion of the Fox Hills Sandstone stratigraphy and depositional environment in a regional context and a comparison of the beach placers with other deposits.

DEPOSITIONAL SETTING AT TITANIUM RIDGE – REGIONAL ANALYSIS

The beach placer deposits at Titanium Ridge conform to the typical succession of regressive sandstones associated with beach placers of the WIS as described by Houston and Murphy (1977). Along the depositional profile, the highest concentrations of heavy minerals appeared to occur in the backbeach deposits; however, some deposits appear in the foreshore as well. The highest concentrations of beach placers observed at Titanium Ridge occur in the backbeach environment as banded exposures of alternating dark, heavy-mineral-rich beds and heavy-mineral-poor sandstones (Figures 16, 17, 18, and 19). As described in the Stratigraphy section above, this suggests that storm events are of great importance for depositing and concentrating heavy minerals. Storm scours lower in the section, and also sigmoidal beds, both found at locations TR-14, TR-13 and TR-04, are interpreted as washover deposit structures due to their similarity to features of modern hurricane deposits (Figure 16), and this indicates the presence of local storms during the Late Cretaceous. Also, the lower parts of the sections at TR-13 and TR-14, interpreted as a foreshore or forebeach environment (Figure 16), are relatively poor in heavy minerals. This is typical in some of the beach placer deposits observed along the WIS in other areas (Houston and Murphy, 1977).

Most of the recent and ancient beach placer deposits observed elsewhere in the world are related to longshore drift, barrier coastlines, and transgressive environments (Clifton, 2006). Beach placers are most commonly observed in forebeach and backbeach depositional environments and are related to storm deposits. At Titanium Ridge, swaley cross-bedding filling storm scours at the basal outcrops of locations TR-13 and TR-14 are indicative of wave-dominated processes (Clifton, 2006). The wave-dominated sedimentary structures suggest a barrier or strandline coast rather than a delta front as described in other areas by Weimer (1973) or an estuarine environment (Roehler, 1993). As presented by McCubbin (1982), a delta coastline is dominated by an interaction of fluvial and marine processes whereas a strandline coast, or a less continuous barrier island coastline, is dominated by marine processes like waves and storms. The north-northwest trend of Titanium Ridge and nearby beach ridges and placers (Figure 15) identified during previous mineral exploration studies in the area generally agrees with the nearby basin-wide correlations of coastlines mapped in the subsurface by Raynolds and Dechesne (2007).

Within the Denver Basin, preservation of the heavy mineral-rich backbeach deposits within the overall regressive sequence of the Fox Hills Sandstone appears unique to Titanium Ridge and nearby associated subsurface trends as delineated by others (WGM, 2000; Pirkle and others, 2012). To our knowledge, beach placers in the Fox Hills Sandstone have not been reported or described elsewhere in the Denver Basin. Several authors have suggested that preservation of heavy minerals in regressive sandstones of the WIS has been associated with short transgressive phases within the overall retreat of the seaway from this area (Houston and Murphy, 1977; Roehler, 1983; Pirkle and others, 2012), preserving the backbeach due to higher accommodation space at those times (Figure 10). Due to its location at the eastern edge of the Denver Basin, the detailed stratigraphic pattern of Titanium Ridge is difficult to unravel due to the limited amount of available exposures in this area. Additionally, geophysical logs associated with oil and gas drilling in this area generally do not contain a record of the upper ~90 m (300 ft) of each well, leaving a data gap that hinders the interpretation of detailed stratigraphic patterns (Dechesne and others, 2011). It is likely, based on the reports of older beach placers associated with the retreat of the WIS described by Houston and Murphy (1977), that the stratigraphic position of the placer deposits at Titanium Ridge is similar to these beach deposits and requires either an aggradation or transgression (high accommodation) to preserve the beach and backbeach depositional environments.

FOX HILLS SANDSTONE BEACH PLACER CHARACTERISTICS AND MINERAL RESOURCE POTENTIAL

The mineralogy observed in the Fox Hills Sandstone just north of the Titanium Ridge trend is similar to that of the western beach placer trend as investigated by others (e.g., Radar) and is also generally similar to the mineralogy of other Cretaceous beach placers in Colorado, Wyoming, and New Mexico. Many of these beach placers, including the beach placers discussed here, contain elevated concentrations of ilmenite, rutile, garnet, zircon, monazite, titanite, epidote, tourmaline, and other minerals (Chenoweth, 1957; Dow and

Batty, 1961; Houston and Murphy, 1962; Houston and Murphy, 1970; Roehler, 1989; McClemore and others, 2016). The beach placers at Titanium Ridge and along the western beach placer trend contain elevated concentrations of critical minerals including titanium, zirconium (and hafnium), and REEs. Allanite, an epidote group mineral containing REEs, was identified in the Fox Hills Sandstone beach placers; it is either reported generally as epidote in other Cretaceous beach placers in Colorado and neighboring states or, is absent.

Previous investigations along the western beach placer trend indicated beach placer thicknesses that ranged from ~0.5 to 13.5 m (2 to 45 ft) with average total heavy mineral (THM) concentrations ranging from 1 to 20% over these intervals. Intervals containing elevated THMs, between ~10 and 50% as estimated from cross sections included in WGM (2000), were more often between ~1.5 and 6 m (5 and 20 ft) thick and bounded by lower grades. In comparison, during the present investigation, heavy mineral concentrations from the automated mineralogy analysis range on average from ~5.5 to 26 vol. % THM (combined garnet, epidote, ilmenite, rutile, titanite, zircon, allanite, monazite, and xenotime percentages) for samples containing disseminated heavy minerals and heavy-mineral laminae, respectively. At most of these sample locations, the visible outcrop thickness of the beach placer (i.e. containing heavy-mineral laminae) ranges from ~1 to 2 m (3 to 6 ft) thick. However, the base of the beach placer was not exposed in outcrop and therefore, the total thickness is unknown.

Laboratory XRF analysis of grab samples collected along the Titanium Ridge beach placer trend detected TiO_2 concentrations ranging from ~8.1 to 11.5% with an average of ~10% (Table 8). These samples were collected within areas where abundant heavy-mineral laminae were visible in hand samples (Figure 23). Analysis of samples collected above these heavy-mineral-rich areas, where the heavy-mineral fraction is disseminated, have average concentrations of 1.7% TiO_2. Due to the unknown thickness and lack of sampling along the entire beach placer deposit, no attempt was made to estimate the potential resource along the Titanium Ridge trend.

At the western beach placer trend, Radar (WGM, 2000) reported a combined measured/indicated resource of 14.2 million tons of heavy minerals at a grade of between 6.8 and 12.3% THMs and a combined ilmenite and rutile grade of 2.4% (Table 5). Inferred resources included an additional 3.3 million tons at a combined ilmenite and rutile grade of 2.5% (Table 5) (WGM, 2000; Radar, 2001). A grade, or average concentration, of ~3.7% TiO_2 was reported for the western beach placer trend. The resource estimate indicates that the average wt. % of ilmenite and rutile is ~2.3% (WGM, 2000). As reported by Pirkle and others (2012), DuPont reported an average grade of the titanium-bearing minerals (e.g., ilmenite and rutile) at only 48% to 50% TiO_2. Later studies attempted to convert the ilmenite to a higher grade synthetic rutile that contains over 80% TiO_2 (Pirkle and others, 2012). It is important to note that these resource and grade estimates do not include the potential northern extension of the western beach placer trend and other trends at Titanium Ridge or its vicinity. Furthermore, these estimates do not include additional resources that may exist in the subsurface to the east of Titanium Ridge.

For comparison purposes, the following estimates were reported for other Cretaceous beach placers in the western U.S. interior (see Tables 4 and 5 for the western beach placer trend resource estimates).

- Point Lookout Sandstone and/or Menefee Formation of the Mesaverde Group, Shiprock group beach placers, south of Cortez, Colorado: estimated 253,500 tons containing an average grade of 0.89% TiO_2 was reported for the Shiprock group beach placers (14 deposits) (Dow and Batty, 1961).
- TiO_2 concentrations reported for Wyoming heavy-mineral deposits, with 41 samples collected from 19 sites, ranged between 1.3 and 31.8% TiO_2 with an average of ~13.4%. These deposits were estimated to contain 21.8 million tons with an average grade of ~5.2% TiO_2 (Dow and Batty, 1961).
- In New Mexico, some individual samples from Apache Mesa in the Cretaceous Point Lookout Sandstone contained TiO_2 concentrations at 15% and the deposit is estimated to contain 132,900 tons at a grade of ~3% TiO_2 (McLemore and others, 2016).
- Dow and Batty (1961) estimate that 33 Cretaceous beach placer deposits in New Mexico contain 4.75 million tons at an average grade of ~12.8% TiO_2.

Laboratory XRF analysis of grab samples collected during this investigation along the Titanium Ridge trend detected ZrO_2 concentrations within the Fox Hills Sandstone beach placer ranging from 1.8 to 4.3 wt. %. Also, analysis of over 100 individual zircons detected hafnium, listed as a critical mineral (Fortier and others, 2018), at concentrations ranging from 3,514 to 10,028 ppm with an average of 6,400 ppm. Radar (WGM, 2000) reported a grade of 0.5% zircon in 14.2 million tons of mineralized sands for the western beach placer trend (Tables 4 and 5). In comparison, ZrO_2 averages of 0.08%, 0.55%, and 2.07% were reported for the 14 deposits in the Shiprock group in Colorado, 19 deposits in Wyoming, and 33 deposits in New Mexico, respectively (Dow and Batty, 1961). The Apache Mesa deposit in New Mexico has an estimated grade of ~2,187 ppm zirconium (McLemore and others, 2016).

The REE-bearing mineral monazite is present in many of the Upper Cretaceous beach placers in Wyoming, New Mexico, and Colorado (Chenoweth, 1957; Dow and Batty, 1961; Houston and Murphy, 1970; Roehler, 1989; McClemore and others, 2016). In the present study, laboratory analysis of the 12 Fox Hills Sandstone samples collected along the Titanium Ridge trend (TR-03 through TR-06) detected TREE concentrations between 637 and 4,909 ppm with an average of 3,326 ppm. These samples were enriched in the LREEs, dominantly cerium and lanthanum. Concentrations of HREEs ranged between 81 and 704 ppm with 53.2 to 461 ppm yttrium. The average REE concentration observed in samples from the Titanium Ridge trend might be similar to other local beach placers such as the ones along the western beach placer trend (Figures 1 and 15) where monazite and allanite were reported but not analyzed for REEs (WGM, 2000). The western beach placer trend assessment reported a combined measured/indicated resource of 14.2 million tons of mineralized sand. If average REE concentrations in this area are similar to the detected concentrations to the east along the Titanium Ridge trend (e.g., 3,326 ppm TREE), this would indicate an estimated potential REE resource of 47,230 short tons for the western beach placer trend. However, the exact percentage of REEs in the western beach placer trend is unknown and therefore, would need further investigation to determine the presence and grade of REEs. In comparison, individual samples from the Point Lookout Sandstone in southwestern Colorado yielded TREE concentrations of 2,692 ppm and the estimated resource grade for the 132,900 ton deposit was 522 ppm TREE (McLemore and others, 2016). For more information, see the summary of REE resources for other deposits by Orris and Grauch (2002).

Additional resources in the Fox Hills Sandstone in this area include garnet, used as an abrasive, and potentially other elements such as thorium, niobium, and others, that may be recovered during the mining of other commodities. Garnet is present at high concentrations in the study area compared to other Cretaceous beach placer deposits in Wyoming, Colorado, and New Mexico. Garnet, mostly almandine, is present within the beach placers to the north of Titanium Ridge at an average concentration of 6.8 vol. %. Garnet grades of 2.9% were estimated along the western beach placer trend on the basis of a laboratory bulk mineral analysis.

The beach placers evaluated along the western beach placer trend may contain a larger potential critical mineral (e.g., titanium, zircon, and REEs) resource compared to other deposits in New Mexico and Wyoming. However, it is difficult to make meaningful comparisons between resource estimates due to the reconnaissance nature of many of the investigations, the differences among estimation methods, and also because some estimates are based on outcrops alone without the benefit of subsurface investigations. Potential resources in beach placers also occur along Titanium Ridge, northward along the Titanium Ridge trend, and could be found in unexplored areas to the east. Future resource evaluations would need to evaluate the viability of mining these deposits at depth. Based on current information, beach placer deposits in different parts of the U.S. and in other countries have lower stripping ratios and higher concentrations and are found in less resistant rocks or in unconsolidated sediments. These factors could make such deposits more economical to mine than the Cretaceous beach placers of the Titanium Ridge area. Although the beach placer in the Fox Hills Sandstone north of I-70 is very friable, it is covered to the west by the Laramie Formation and Quaternary sediments. For comparison to other beach placer deposits, see the resource summary by Elsner (1997) for deposits in the southeastern U.S. and other areas around the world.

Future Mineral Exploration

The past exploration activities conducted in this region indicate that there are several beach placer deposits that likely extend over several kilometers that follow paleoshoreline trends but that occur at depth. Pirkle and others (2012, page 39) hypothesize that if the *"St. Catherines Island beach [Georgia] is a valid model for the Titanium Ridge beach, the Titanium Ridge heavy-mineral placer can be expected to be a shoestring bonanza deposit with many kilometers of continuity along strike and limited continuity along dip (perpendicular to the strand)."*

Because of the nature of these deposits as recorded in the southeast U.S. (Figure 4) and elsewhere in the world, it is expected that additional pods of beach placers occur within the paleoshoreline deposits of the Fox Hills Sandstone. Drilling activities should target the paleoshoreline trends; however, coastal landforms can be heterogeneous and therefore, these trends should be used as a general guide.

Past exploration activities relied on drilling, ground-based geophysics, and aerial geophysical surveys. Geophysical tools were used to log natural gamma and electrical susceptibility in borings. Reportedly, during past investigations, the natural gamma borehole tool was useful and assisted with determining the mineralized zone and lithology boundaries. A borehole magnetic susceptibility log was also collected and apparently was an effective tool in determining the presence of heavy minerals. Based on the success of the magnetic measurements, surface magnetometer geophysical measurements were made to direct future drilling efforts. Although the use of this tool was generally successful, the surface magnetometer reportedly provided occasional false positive and false negative results. For example, drilling encountered heavy minerals in areas where no mineralization was detected using the surface magnetometer data and vice-versa.

Due to the relative success of using the magnetometer, an airborne magnetic survey was conducted during exploration activities in the late 1990s (Table 2) over an area where the Fox Hills Sandstone crops out or is known to exist beneath less than ~30 to 60 m (100 to 200 ft) of overlying deposits. This survey included an area of ~190 km (120 miles) by 40 km (25 miles with a line spacing of ~1.5 to 3 km (1 to 2-miles). The survey area extended ~60 km (40 miles) south of Limon (near Forder), north, to an area west of Ft. Morgan (near Orchard). During past exploration activities, several subsurface anomalies indicated that the western beach placer trend may extend several miles to the northwest and other anomalies were detected north of Titanium Ridge, east of Titanium Ridge, and in areas to the south. As indicated above, the magnetic data could provide false positives and negatives and therefore, these deposits would have to be verified in the field.

During the present study, hand samples were analyzed using a handheld XRF (Table 6). The results were assumed to be semi-quantitative and were helpful when determining relative differences in titanium, zirconium, and other element concentrations. When compared with the laboratory results, the handheld XRF successfully measured the elevated concentrations of titanium, zirconium, and other key elements. These results demonstrate that the handheld XRF can be used to provide a rapid field assessment in areas where heavy-mineral layers are not apparent.

SUMMARY

The Fox Hills Sandstone in the eastern Denver Basin contains beach placers associated with paleoshorelines of the receding Late Cretaceous WIS. Analysis of outcrops in the area suggests that clastic sediments of the Fox Hills Sandstones were deposited within a beach environment during the Late Cretaceous. The sandstone beds form eastward-stepping shoreface sequences with the underlying marine Pierre Shale and overlying continental deposits of the Laramie Formation.

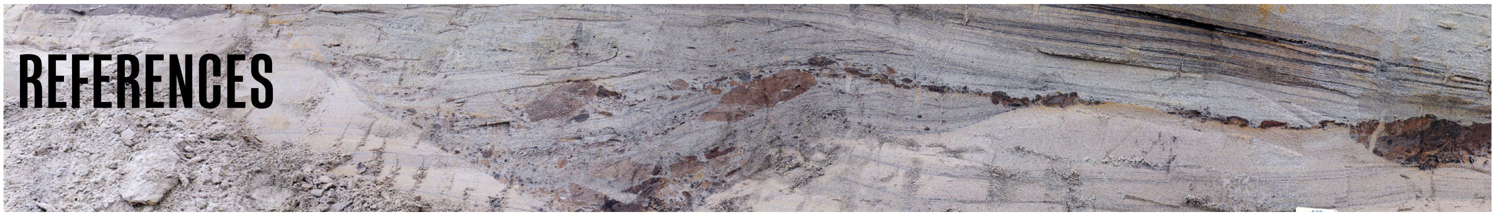
Facies observed in the Fox Hills Sandstone during this study include forebeach, backbeach, and washover deposits. Beach placer deposits appear to be associated with backbeach storm deposits and potentially with the portion of the upper forebeach lying in the swash zone. Trace fossils of *Ophiomorpha* and other trace escape burrows indicate a shallow marine environment. The lack of dune deposits indicates that there was either a period of erosion or that the dunes inshore from the backbeach were localized features. Alternatively, washover deposits may represent storm events that inundated a vegetated backbeach. Capping sandstones described as potential eolian sand dune deposits by others may actually be storm washover deposits and be associated with a transgressive cycle prior to burial by the continental deposits of the Laramie Formation.

Several paleoshoreline trends containing beach placers were identified within the Fox Hills Sandstone in the study area. This includes a western beach placer trend where an economic assessment was completed during prior investigations. Other trends include the beach placer at Titanium Ridge and possible trends to the east of the ridge. Few outcrops of the beach placers exist in the study area and past exploration identified these deposits at depth within the Fox Hills Sandstone. Drilling and geophysical exploration programs identified potential extensions of these paleoshoreline deposits and beach placers for many miles (e.g., ~20 km [14 miles] and some could be longer) along the northwest-oriented paleoshoreline.

The Fox Hills Sandstone beach placers contain elevated concentrations of the critical minerals titanium, zirconium, REEs, and potentially hafnium. Heavy minerals of the beach placers include ilmenite, rutile, titanite, garnet (almandine), epidote, and zircon with minor amounts of REE-bearing allanite and monazite. An economic assessment by others (WGM, 2000; Radar, 2001; Pirkle and others, 2012) along the western beach placer trend targeted the titanium-bearing minerals, zircon, and garnet. This assessment reported the following resources over a ~5.5 km (3.5 mile) trend: a measured resource of 7.2 million tons of mineralized sands with a grade of 2.2% ilmenite, 0.1% rutile, 3.1% garnet, and 0.5% zircon; an indicated resource of 7.0 million tons with a grade of 2.3% ilmenite, 0.1% rutile, 3.0% garnet, and 0.5% zircon; and an inferred resource of 3.3 million tons of mineralized sand at a grade of 2.4% ilmenite, 0.1% rutile, 3.1% garnet, and 0.5% zircon.

Additional exploration activities in the area discovered beach placer trends at Titanium Ridge and in other areas. Analysis of samples collected along the Titanium Ridge trend on SLB lands during the present study detected elevated concentrations of titanium, zirconium, and garnet similar to the western beach placer trend evaluated by others. Analysis of these samples from within the beach placer deposit also detected elevated concentrations of REEs associated with the minerals allanite, monazite, and xenotime. These REE concentrations also may occur in the other beach placer deposits in the area. The beach placers likely follow paleoshoreline trends (~N 20° W) within the Fox Hills Sandstone, trends that could extend to the north and south of known deposits.

Previous economic assessments of a small portion of the beach placers in the Fox Hills Sandstone along the western beach placer trend indicate that they may contain a larger resource than the preliminary estimates made of other Cretaceous beach placers in Colorado as well as Wyoming and New Mexico. However, the Fox Hills deposits of this study will be more difficult to extract and will likely not be economical when compared with beach placer resources that occur and are mined in the southeast U.S. and other parts of the world. Future exploration efforts may indicate a larger resource in the study area at depth and along the northwest paleoshoreline trends.



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Appendices

Appendix A

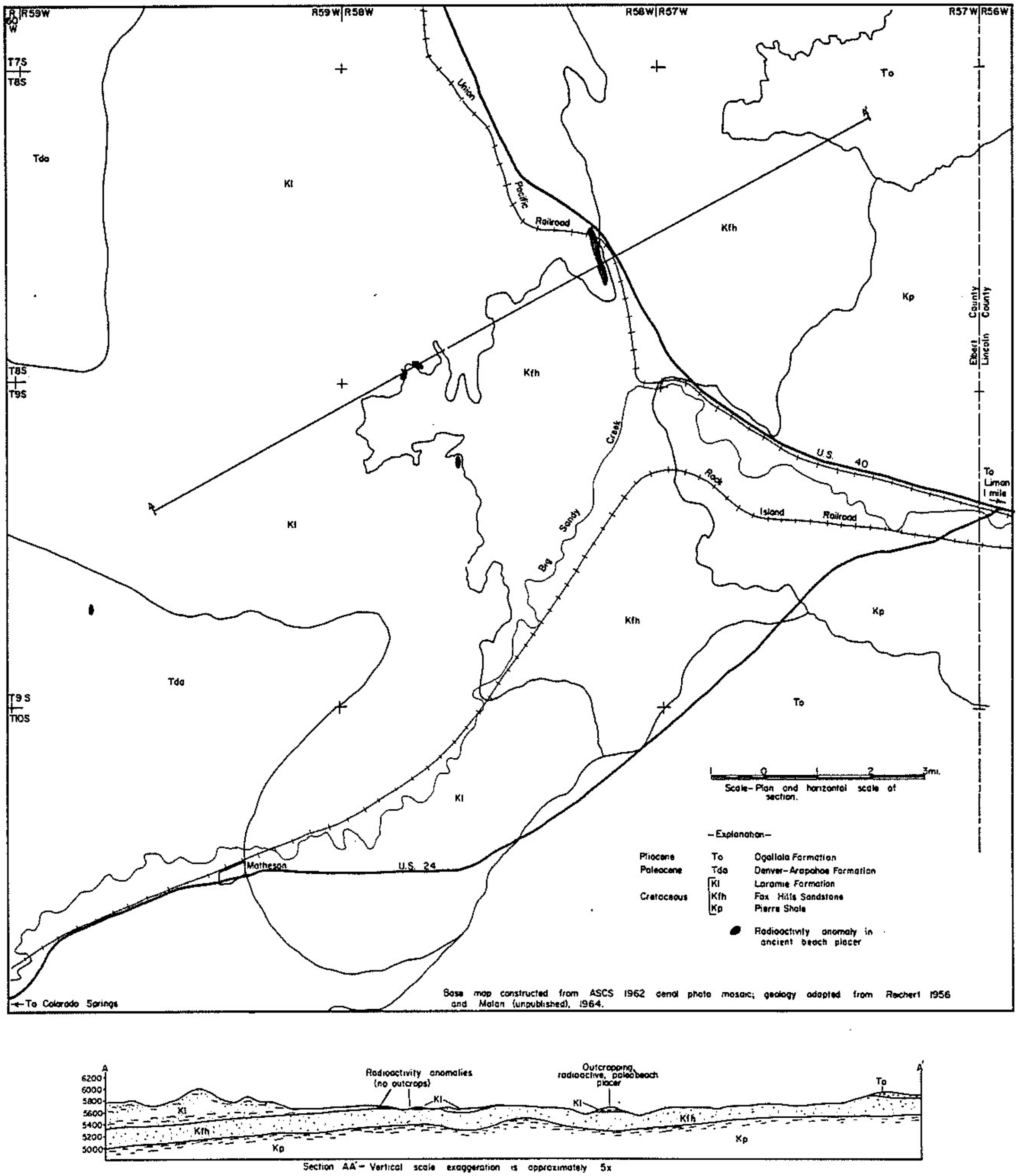
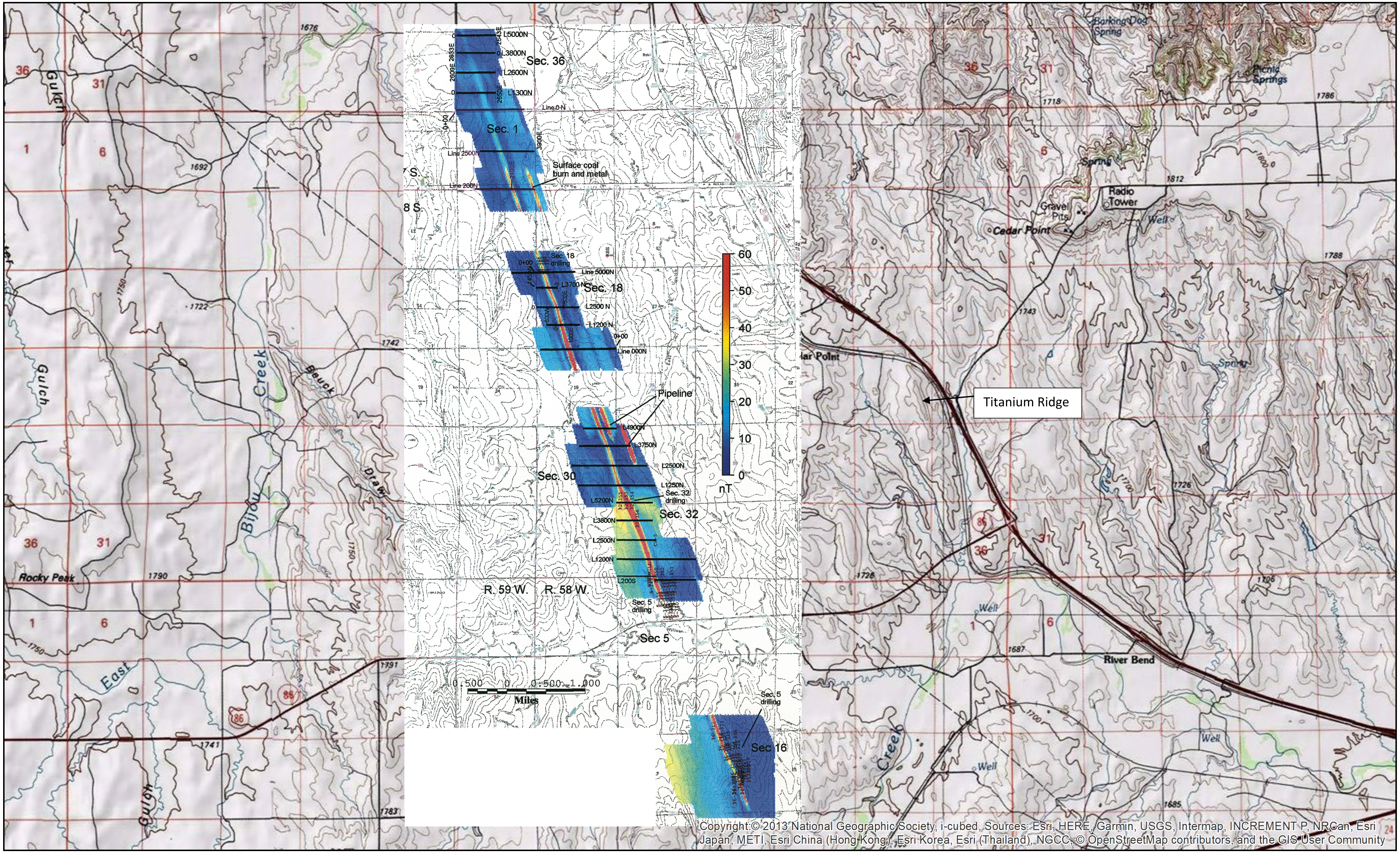


Figure 42. Generalized Geologic Map and Section of the Limon Locality, Denver Basin, Elbert County, Colorado

Appendix A – Map from original 1956 AEC Survey (Malan, R.C., 1965, Geology of Uranium Deposits in the Northern Part of the Rocky Mountain Province of Colorado, United States Atomic Energy Commission, Grand Junction Office, Production Evaluation Division Resource Appraisal Branch, Issue Date May 1983, October 1965, AEC-RD-14, 102 p.)



Appendix A – Map of beach placer trends in the Fox Hills Sandstone west of the I-70 and Highway 86 junction, as delineated by a magnetic survey during past exploration activities (figure from a CGS internal file; also see WGM [2000] for a description and cross sections shown on this figure). Southern portion of the trend is exposed on Colorado State Land Board land (section 16) at the surface and is buried by overlying deposits to the north. nT = nanoTeslas, warmer colors indicate higher nT and/or magnetic minerals, trend is about 16 km (10 miles) long. Public Land Survey System (PLSS) sections are approximately 1.6 by 1.6 km (1 by 1 mile).

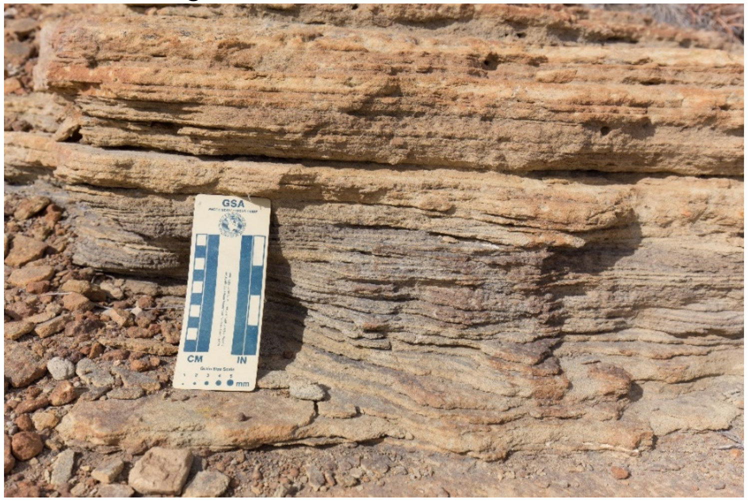
Appendix B

Photo log. Scale card in many of these photos is ~16.5 cm (6.5 inches) long.

1: Southeast edge of Titanium Ridge, channel in forebeach deposits of Fox Hills Sandstone. Beach placer exposed at the top.

2: Close-up of channel described in photo 1.

3: Oxidized beach placer, Fox Hills Sandstone, southeast edge at the top of Titanium Ridge.



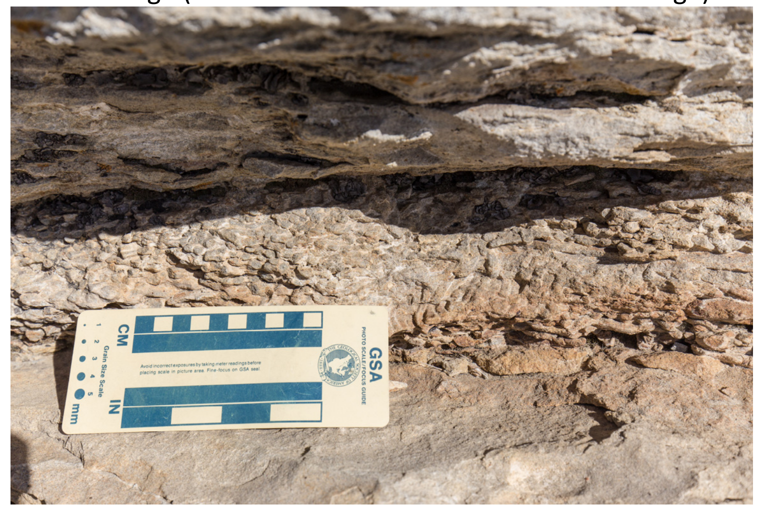
4: Fox Hills Sandstone capping southeast portion of Titanium Ridge. Small ball-like iron-rich concretions erode from sandstone.

NOTE: All photos by Mike O'Keeffe unless otherwise noted.

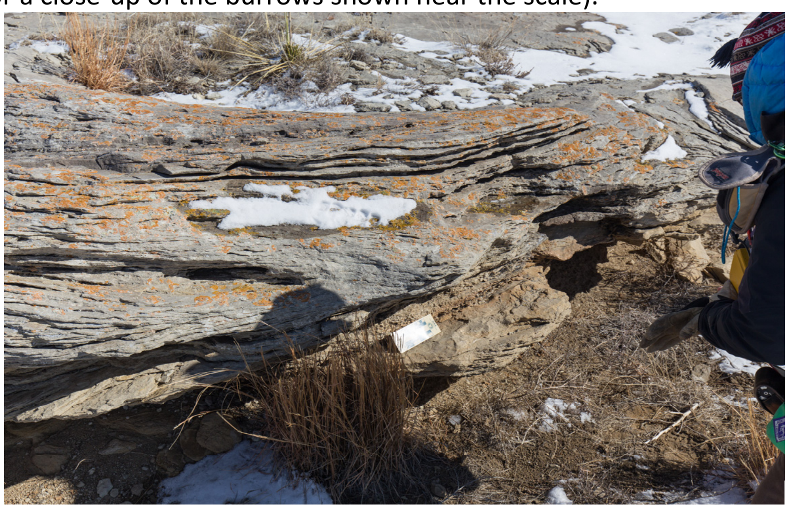
Photo log. Scale card in many of these photos is ~16.5 cm (6.5 inches) long.

5: Plant fossils in backbeach/washover deposits, Fox Hills Sandstone, Titanium Ridge.

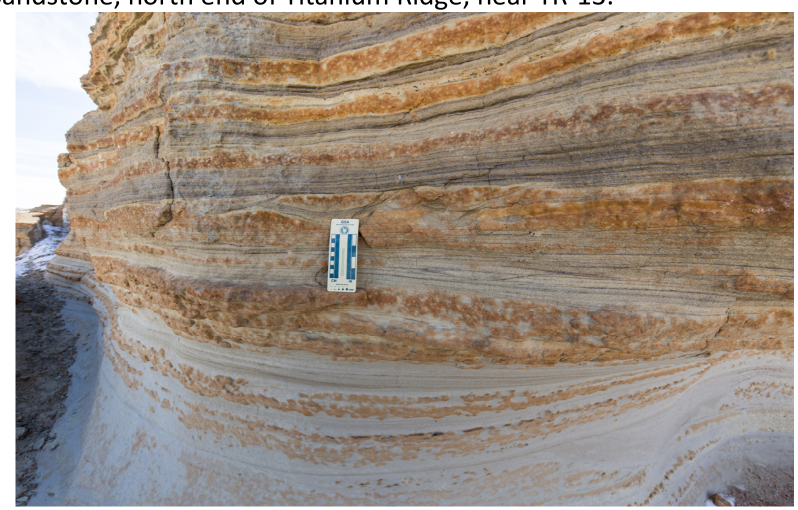
6: Horizontal burrows within upper Fox Hills Sandstone capping areas of Titanium Ridge (west of TR-13 on the west side of the ridge).



7: Fox Hills Sandstone capping areas of Titanium Ridge (see photo 6 for a close-up of the burrows shown near the scale).



8: Beach placer deposits overlying forebeach sands, Fox Hills Sandstone, north end of Titanium Ridge, near TR-13.



NOTE: All photos by Mike O'Keeffe unless otherwise noted.

Photo log. Scale card in many of these photos is ~16.5 cm (6.5 inches) long.

9: Close-up of photo 8 showing heavy mineral laminae (dark bands).

10: Upper Fox Hills Sandstone beach placers, north end, Titanium Ridge.

11: Fox Hills Sandstone with beach placers and backbeach deposits, east side of Titanium Ridge, at TR-14.

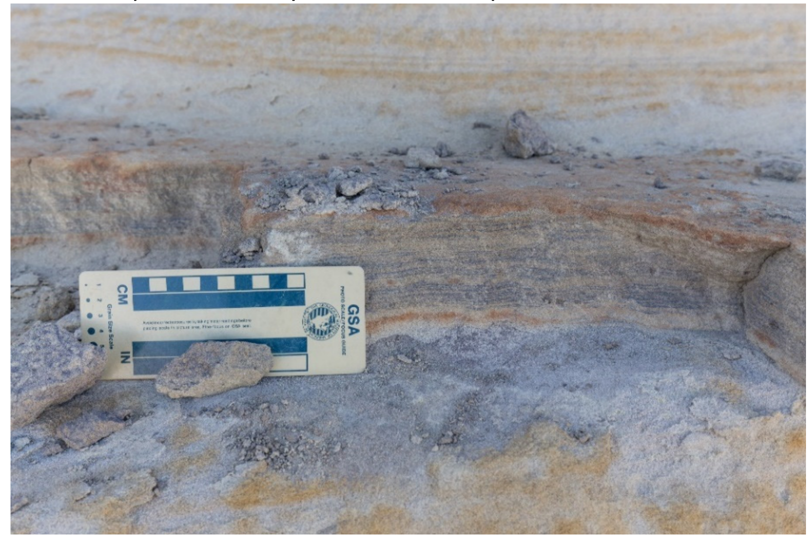
12: Close-up of photo 11.

NOTE: All photos by Mike O'Keeffe unless otherwise noted.

Photo log. Scale card in many of these photos is ~16.5 cm (6.5 inches) long.

13: Fox Hills Sandstone, southeast side of Titanium Ridge, forebeach deposits with a small ~8 cm (~3.1 inches) heavy-mineral-rich layer just below the scale (middle of photo).

14: Close-up of the heavy-mineral bed in photo 13.

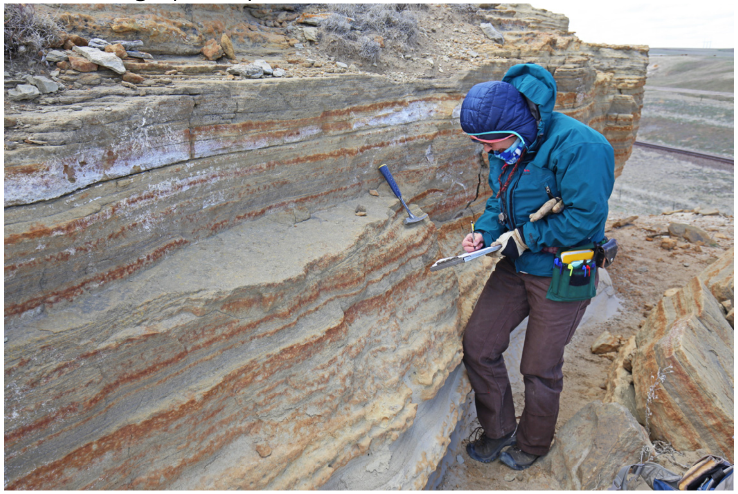


14: Panorama from the northwest point of Titanium Ridge looking northwest. Railroad and I-70 in the background.

NOTE: All photos by Mike O'Keeffe unless otherwise noted.

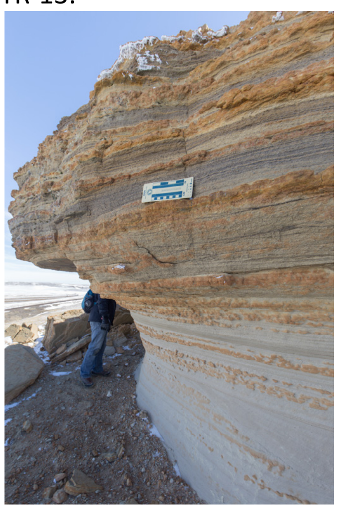
Photo log. Scale card in many of these photos is ~16.5 cm (6.5 inches) long.

15: Beach placer deposits in Fox Hills Sandstone at the northeast end of Titanium Ridge (TR-13). Marieke Dechesne for scale.



16: Beach placers capped by backbeach/washover deposits, Fox Hills Sandstone, east side of Titanium Ridge at TR-14. Hammer is ~41 cm (16 inches) long.

17: Beach placer underlain by foreshore deposits, northern end of Titanium Ridge near TR-13.



18: Same as photo 17.

NOTE: All photos by Mike O'Keeffe unless otherwise noted.

Photo log. Scale card in many of these photos is ~16.5 cm (6.5 inches) long.

19: Fox Hills Sandstone ~95 m (~312 ft) east-northeast of TR-03.

20: Close-up of outcrop base in photo 21 showing heavy-mineral laminae. Hammer is ~41 cm (~16 inches) long.

21: Northern portion of outcrop shown in photo 19.

22: Beach placer in the Fox Hills Sandstone at TR-02 (see handheld XRF screening results table, near TR-03).

NOTE: All photos by Mike O'Keeffe unless otherwise noted.

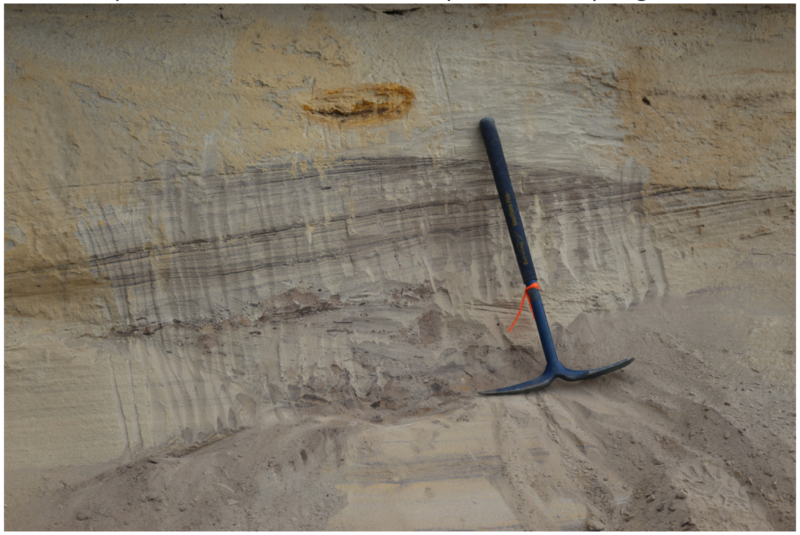
Photo log. Scale card in many of these photos is ~16.5 cm (6.5 inches) long.

<table>
<tr>
<td>23: Beach placer with heavy-mineral laminae, Fox Hills Sandstone at TR-04.
</td>
<td>24: Close-up of unit above the laminae shown in photo 23 with rip-up clasts (potential soil rip-ups with root traces).
</td>
</tr>
<tr>
<td>25: Close-up of rip-up clast from photo 24. Note smaller rip-up clasts in the lower right corner.
</td>
<td>26: Beach placer near TR-03. Hammer is ~41 cm (16 inches) long.
</td>
</tr>
</table>

NOTE: All photos by Mike O'Keeffe unless otherwise noted.

Photo log. Scale card in many of these photos is ~16.5 cm (6.5 inches) long.

27: Beach placer, Fox Hills Sandstone, prior to sampling at TR-05.



28: Close-up of photo 27 showing rip-up clasts below heavy-mineral laminae.

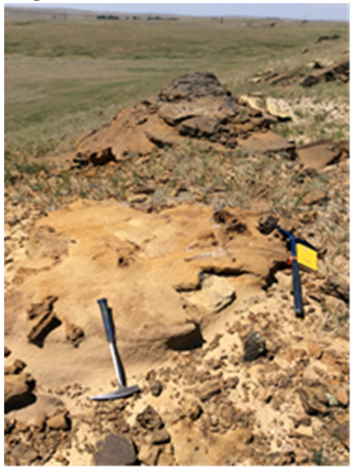
29: Beach placer, Fox Hills Sandstone, prior to TR-06 sampling. Hammer is ~41 cm (16-inches) long.

30: Close-up of photo 29 showing the heavy-mineral laminae.

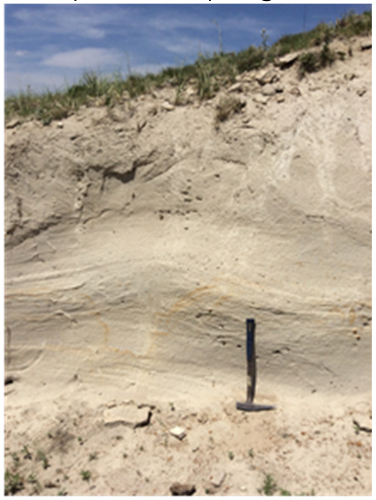
NOTE: All photos by Mike O'Keeffe unless otherwise noted.

Photo log. Scale card in many of these photos is ~16.5 cm (6.5 inches) long.

31: Top of the Fox Hills Sandstone with abundant iron oxide-cemented sand beds and *Ophiomorpha* burrows at TR-12. Hammer is ~41 cm (16 inches) long.



32: Fox Hills Sandstone at TR-01 (see handheld XRF screening results table). Hammer is 41 cm (~16-inches) long.



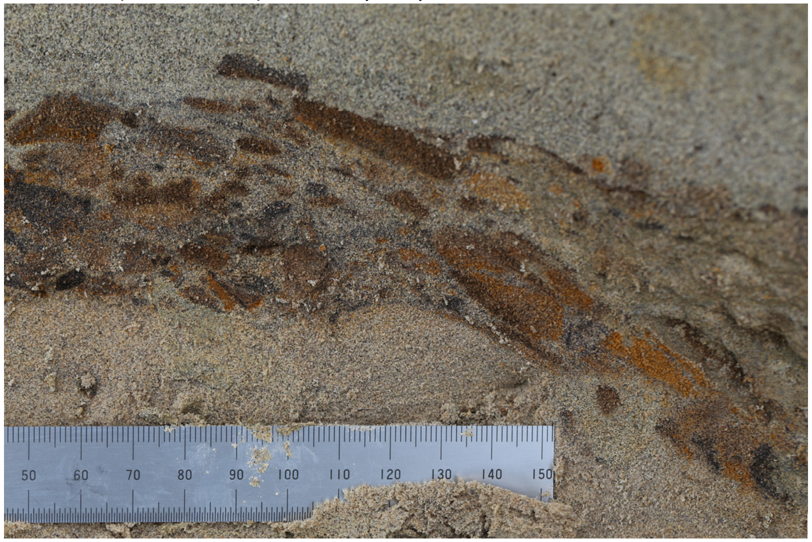
33: Fox Hills Sandstone near TR-05.

34: Undulatory erosional surface in the Fox Hills Sandstone, close-up of photo 33. Note clasts on the erosional surface just below the scale.

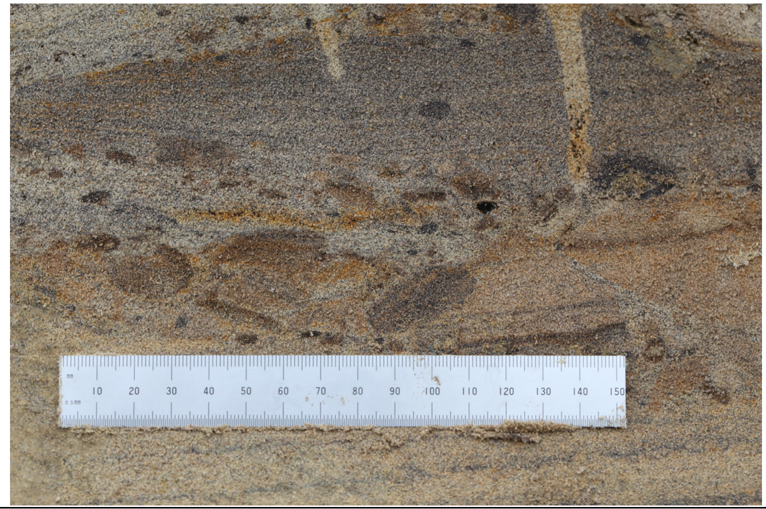
NOTE: All photos by Mike O'Keeffe unless otherwise noted.

Photo log. Scale card in many of these photos is ~16.5 cm (6.5 inches) long.

35: Clasts (scale in cm), close-up of photo 34.

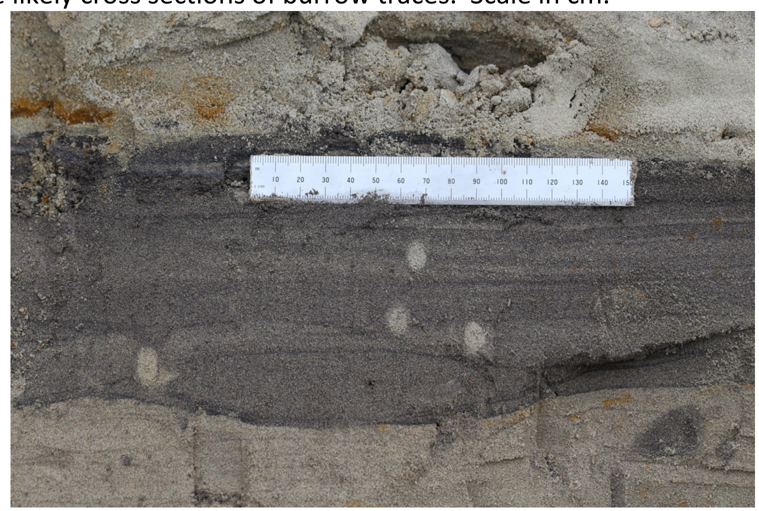


36: Clasts, close-up of photo 34, burrows on the top of the photo. Scale in cm.



37: Close-up of photo 34 and wide view of photo 36 showing heavy mineral- rich clasts and burrows. Scale in cm.

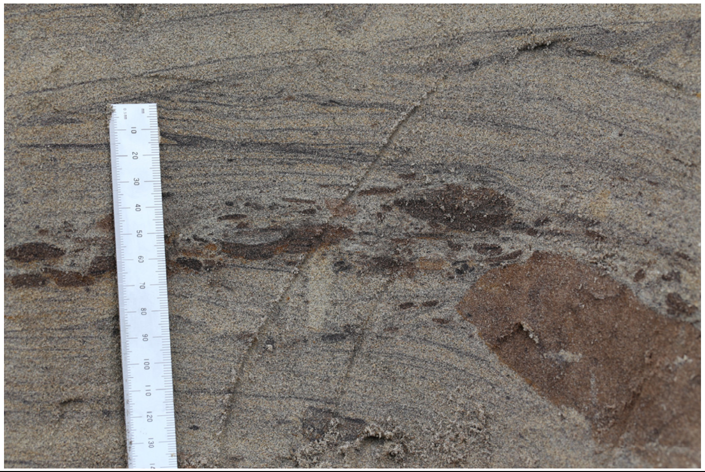
38: 15 cm (6-inch) thick heavy-mineral bed near TR-05. White spots are likely cross sections of burrow traces. Scale in cm.



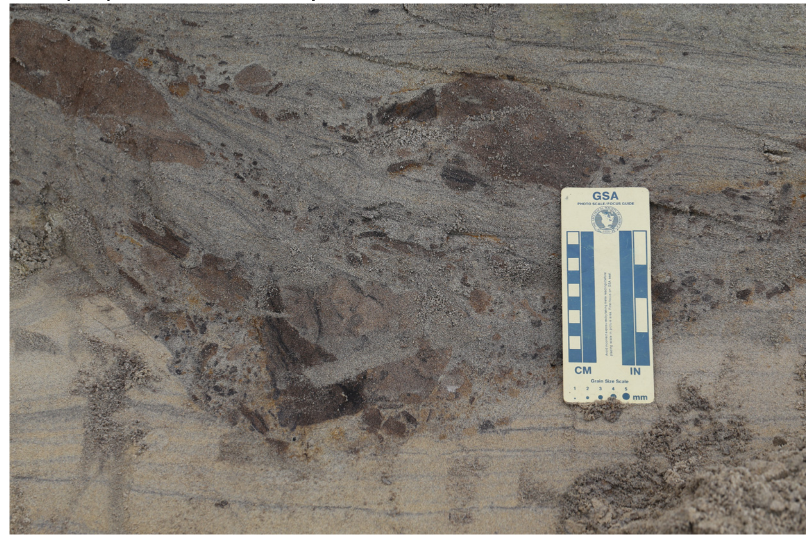
NOTE: All photos by Mike O'Keeffe unless otherwise noted.

Photo log. Scale card in many of these photos is ~16.5 cm (6.5 inches) long.

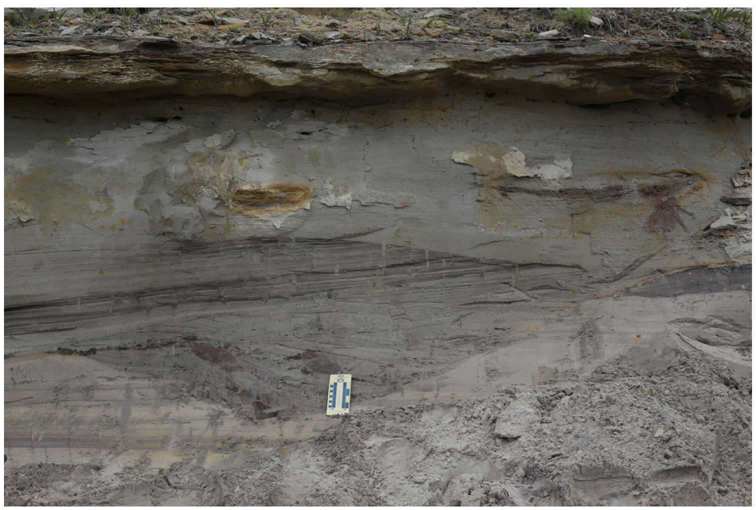
39: Rip-up clasts and heavy-mineral laminae at TR-05. Rip-up clasts are derived from older beach placer (heavy-mineral-rich) deposits. Scale in cm.



40: Rip-up clasts and heavy-mineral laminae at TR-05.



41: Fox Hills Sandstone, wide-angle view of photos 39 and 40, at TR-05.



42: Fox Hills Sandstone near TR-06. Note steep erosional surface with dark clasts (rip-ups?) containing heavy minerals (large clast was analyzed using handheld XRF; see results for TR-19 in table).

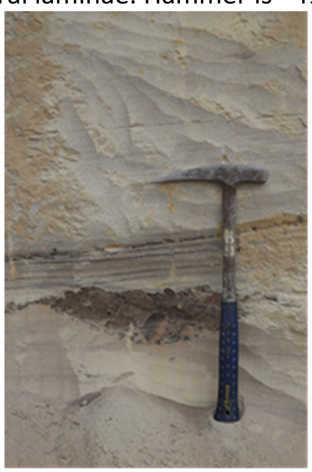
NOTE: All photos by Mike O'Keeffe unless otherwise noted.

Photo log. Scale card in many of these photos is ~16.5 cm (6.5 inches) long.

43: Close-up of photo 42.

44: Close-up of large dark clast shown in photos 42 and 43 after sampling (see handheld XRF screening results for TR-19 in table).

45: Fox Hills Sandstone, clasts in small paleoswale near TR-05 with overlying heavy-mineral laminae. Hammer is ~41 cm (16 inches) long.

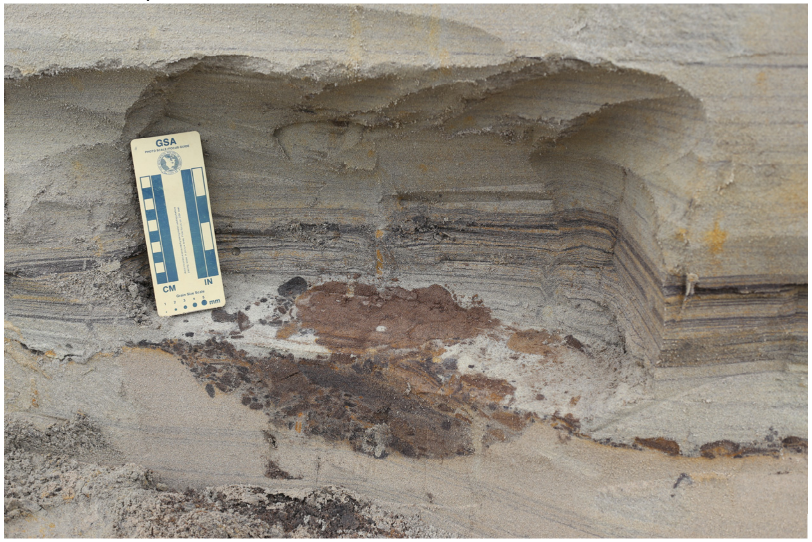


46: Same as photo 45 after excavation of the paleoswale.

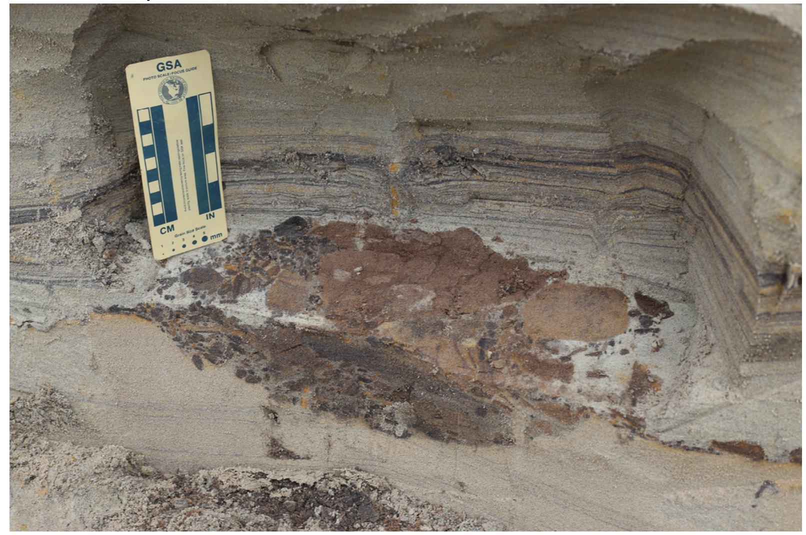
NOTE: All photos by Mike O'Keeffe unless otherwise noted.

Photo log. Scale card in many of these photos is ~16.5 cm (6.5 inches) long.

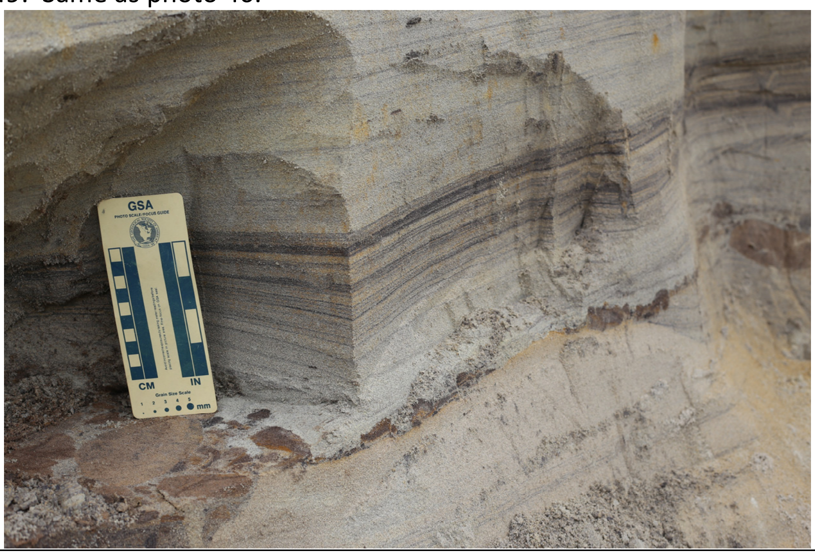
47: Same as photo 46.



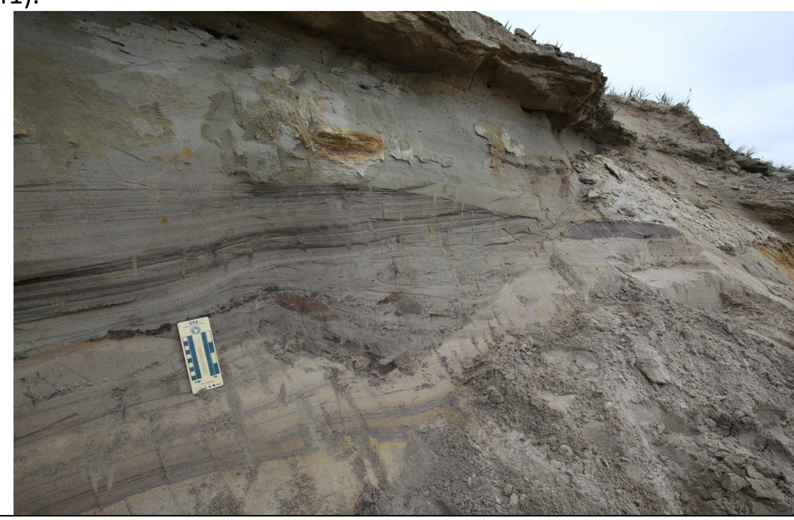
48: Same as photo 46.



49: Same as photo 46.



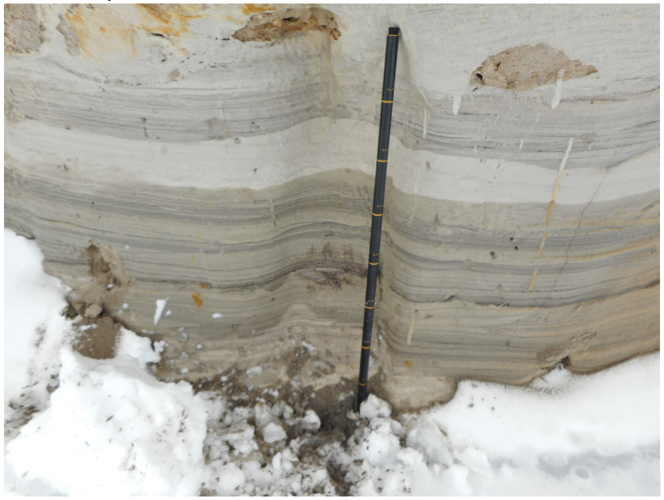
50: Wide-angle view of Fox Hills Sandstone at TR-05 (see photos 39-41).



NOTE: All photos by Mike O'Keeffe unless otherwise noted.

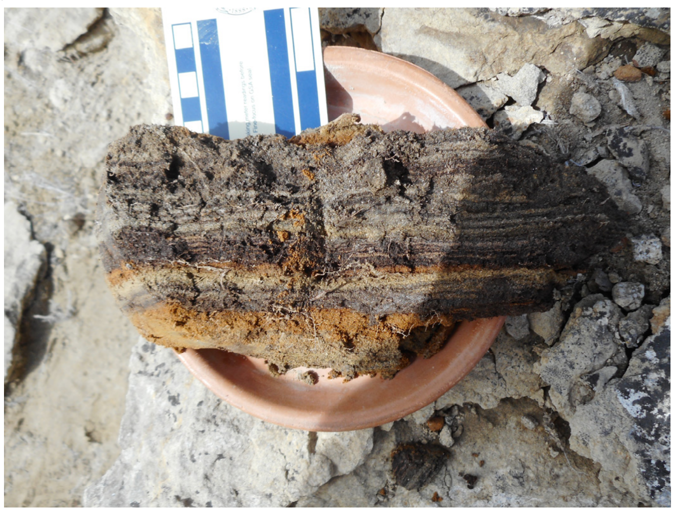
Photo log. Scale card in many of these photos is ~16.5 cm (6.5 inches) long.

51: Sample TR-03 REF1 (see handheld XRF screening results table) (photo: S. Keller).



52: Sample TR-05 REF1 (see handheld XRF screening results table) (photo: S. Keller).

53: Sample TR-07 REF 2 (see handheld XRF results table) (photo: S. Keller).

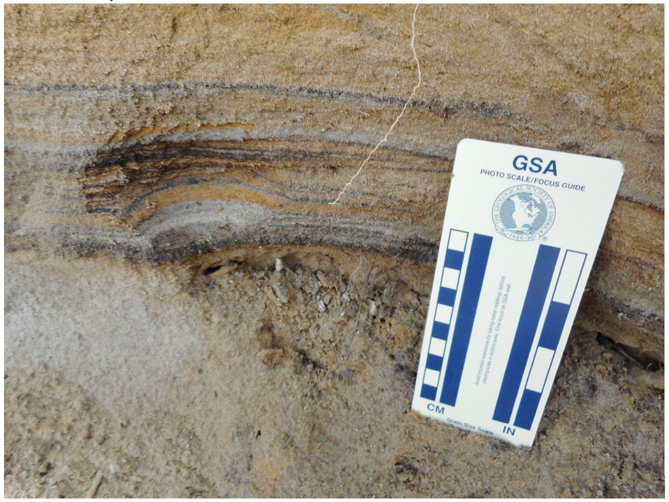


54: Sample TR-07 REF3 (see handheld XRF screening results table) (photo: S. Keller).

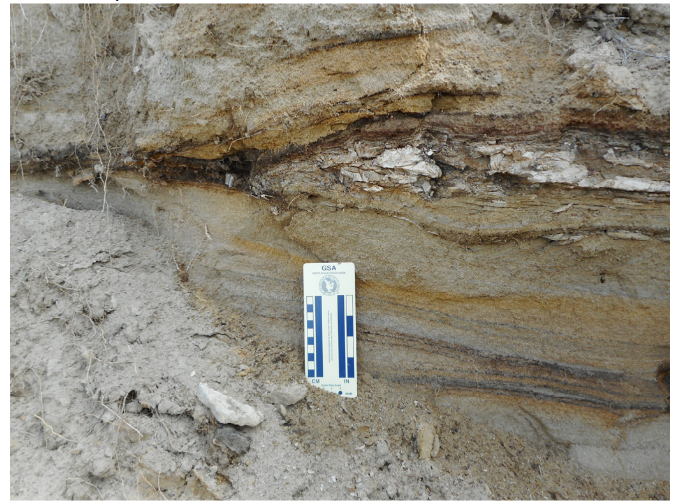
NOTE: All photos by Mike O'Keeffe unless otherwise noted.

Photo log. Scale card in many of these photos is ~16.5 cm (6.5 inches) long.

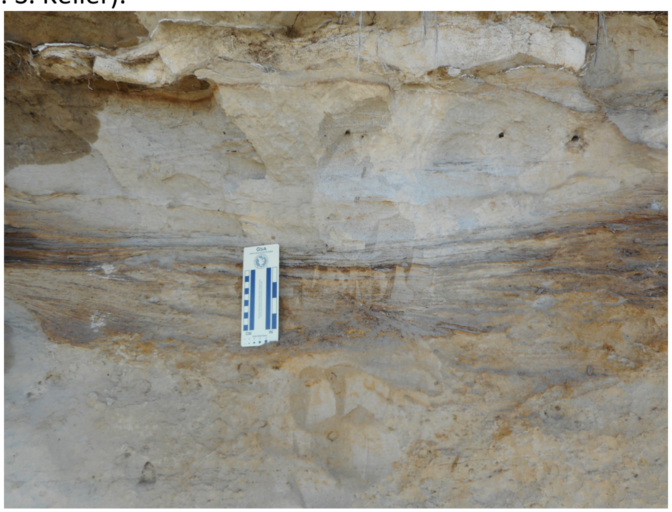
55: Sample TR-07 REF3A (see handheld XRF screening results table) (photo: S. Keller).



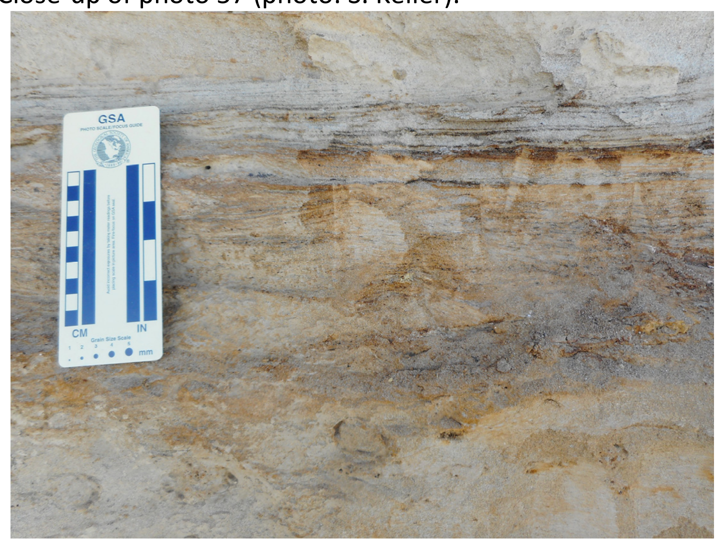
56: Sample TR-07 REF4 (see handheld XRF screening results table) (photo: S. Keller).



57: Sample TR-08 REF1 (see handheld XRF screening results table) (photo: S. Keller).



58: Close-up of photo 57 (photo: S. Keller).



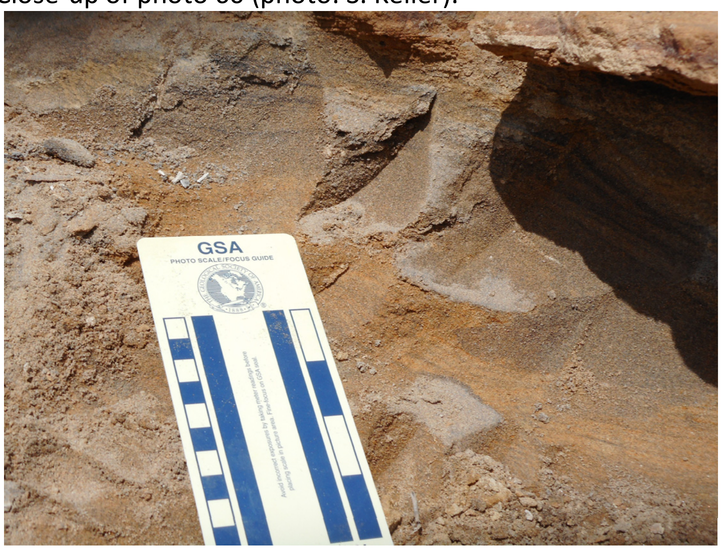
NOTE: All photos by Mike O'Keeffe unless otherwise noted.

Photo log. Scale card in many of these photos is ~16.5 cm (6.5 inches) long.

59: Sample TR-08 REF3 (see handheld XRF screening results). Shovel is ~1.2 meters (3.8 feet) tall (photo: S. Keller).

60: Sample TR-10 (see handheld XRF screening results) (photo: S. Keller). Bar in lower right corner is ~0.15 meters (0.5 feet).

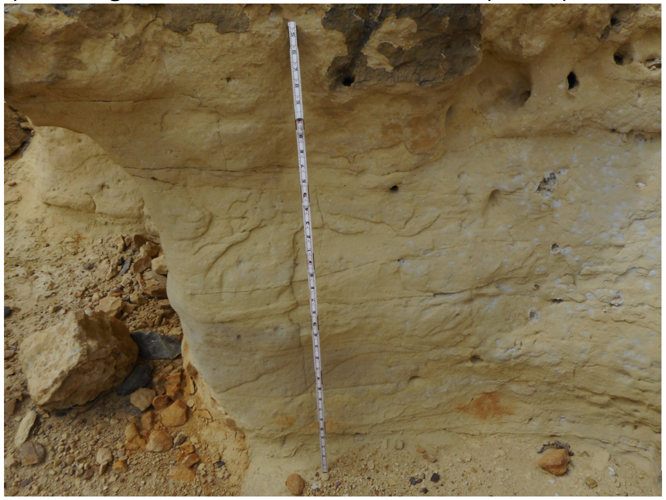
61: Close-up of photo 60 (photo: S. Keller).



62: Sample TR-11 REF (see handheld XRF screening results table). Shovel is ~1.2 meters (3.8 feet) tall (photo: S. Keller).

NOTE: All photos by Mike O'Keeffe unless otherwise noted.

Photo log. Scale card in many of these photos is ~16.5 cm (6.5 inches) long.

<table>
<tr>
<td>63: Sample TR-12 REF1 (see handheld XRF screening results table) (photo: S. Keller). Folding rule extended to ~1.2 meters (4 feet).
</td>
<td>64: Sample TR-12 REF2 (see handheld XRF screening results) (photo: S. Keller). Folding rule extended to ~1.2 meters (4 feet).
</td>
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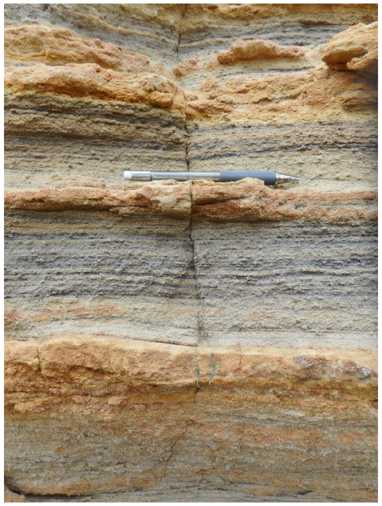
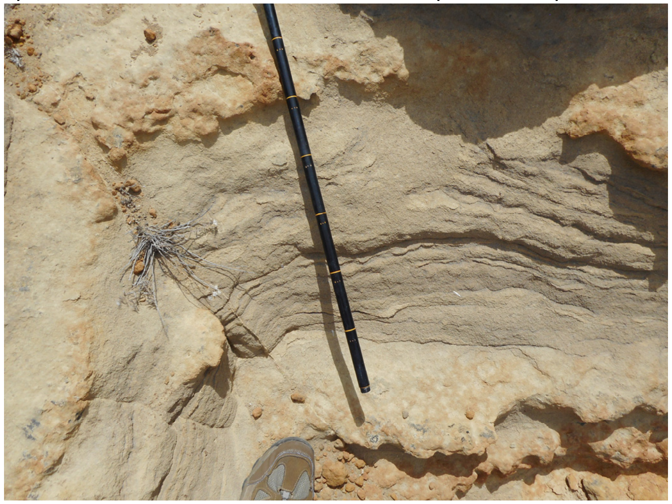
<td>65: Sample TR-13 REF1 (see handheld XRF screening results) (photo: S. Keller).
</td>
<td>66: Sample TR-13 REF2 (see handheld XRF screening results) (photo: S. Keller). Rod divisions are 10 centimeters (~4 inches).
</td>
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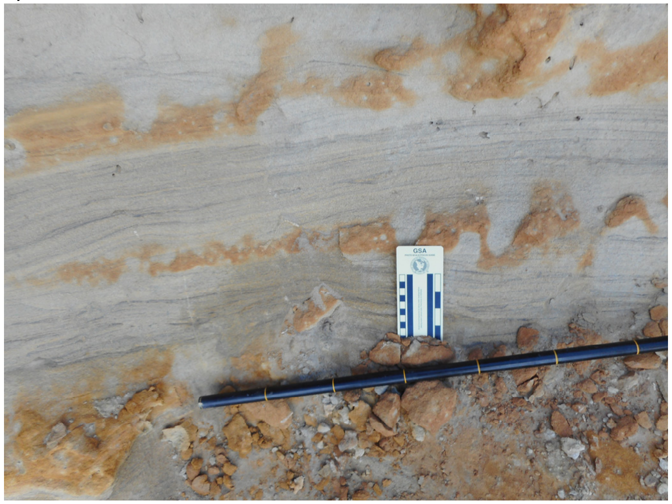
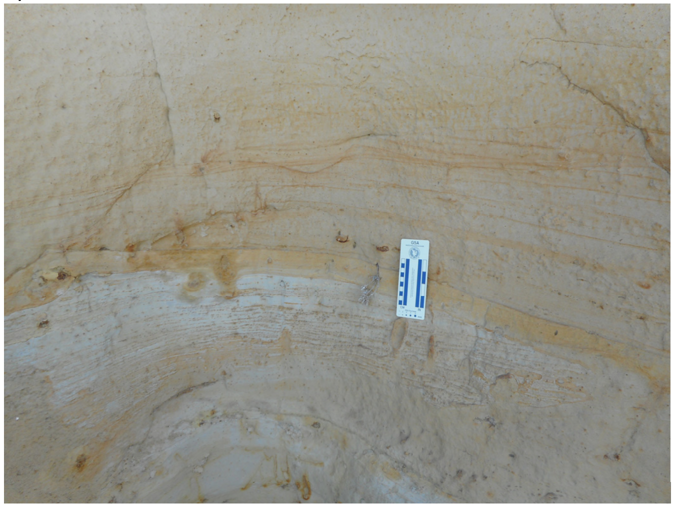
NOTE: All photos by Mike O'Keeffe unless otherwise noted.

Photo log. Scale card in many of these photos is ~16.5 cm (6.5 inches) long.

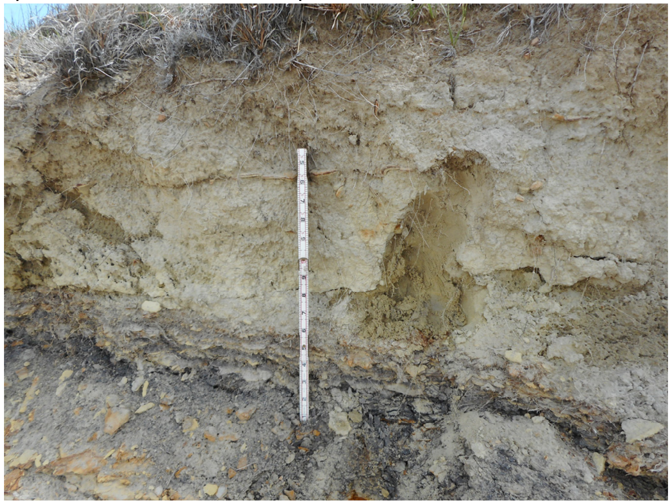
67: Sample TR-14 REF1 (see handheld XRF screening results) (photo: S. Keller).



68: Sample TR-15 REF1 (see handheld XRF screening results) (photo: S. Keller).



69: Sample TR-15 REF2 (see handheld XRF screening results) (photo: S. Keller). Scale is ~0.47 meters (1.55 feet).



70: Sample TR-16 REF1 (see handheld XRF screening results) (photo: S. Keller). Shovel is ~1.2 meters (3.8 feet) tall.

NOTE: All photos by Mike O'Keeffe unless otherwise noted.

Photo log. Scale card in many of these photos is ~16.5 cm (6.5 inches) long.

<table>
<tr>
<td>71: Sample TR-17 REF1 (see handheld XRF screening results) (photo: S. Keller). Shovel is ~1.2 meters (3.8 feet) tall.
</td>
<td>72: Sample TR-17 REF3 (see handheld XRF screening results) (photo: S. Keller).
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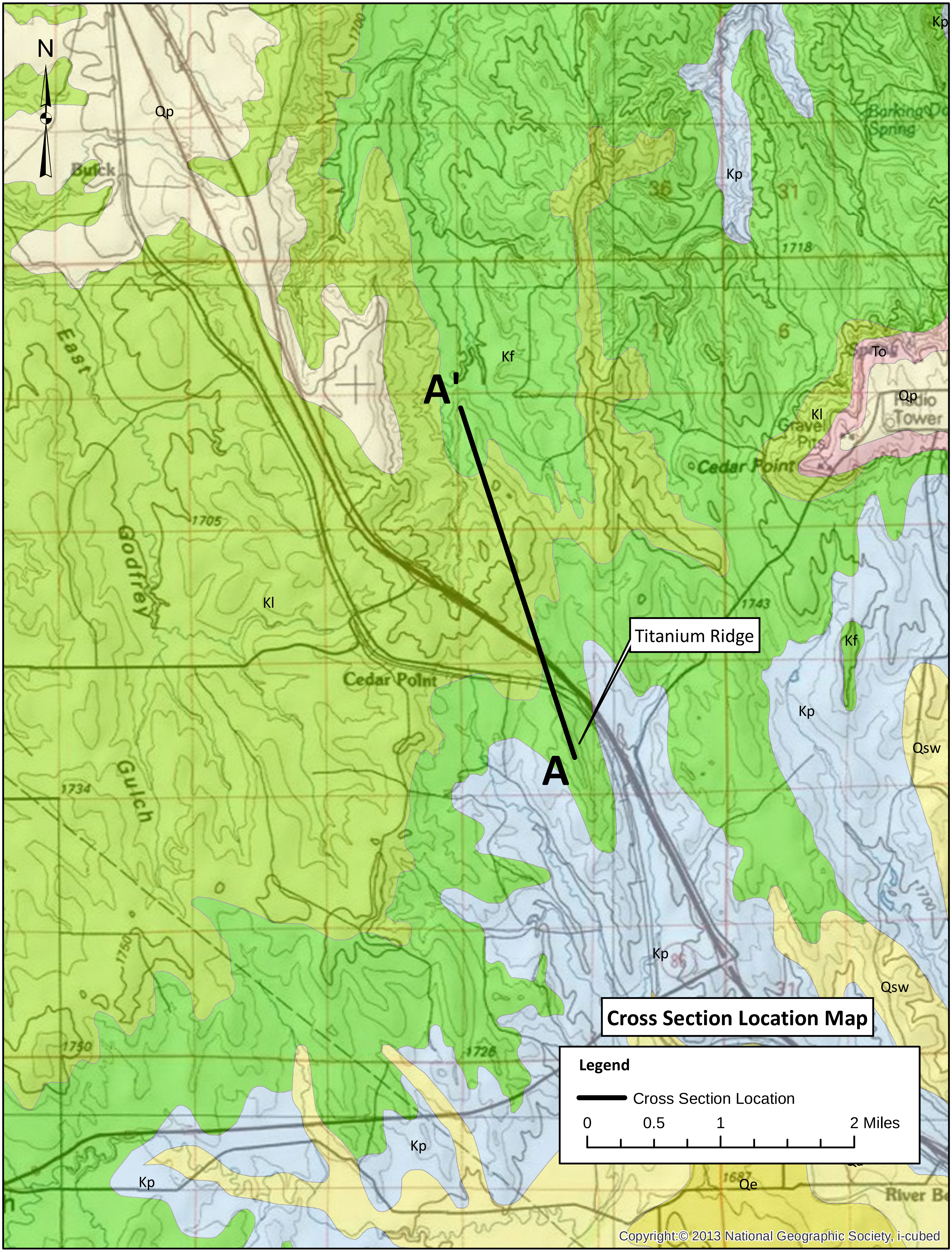
NOTE: All photos by Mike O'Keeffe unless otherwise noted.

Appendix C


N
Cross Section Location Map
Legend
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Qp
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Cedar Point
Buick
Barking Dog Spring
Radio Tower
Gravel Pit
River Bend
1705
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Copyright:© 2013 National Geographic Society, i-cubed

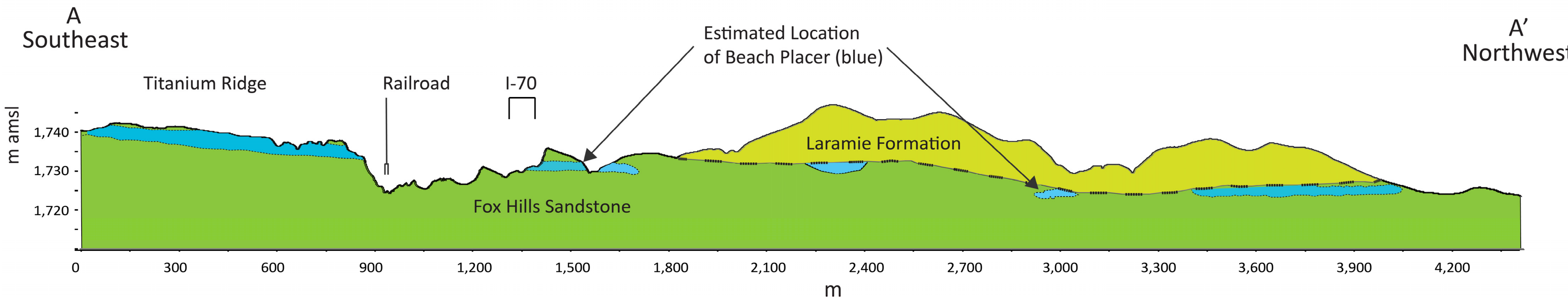
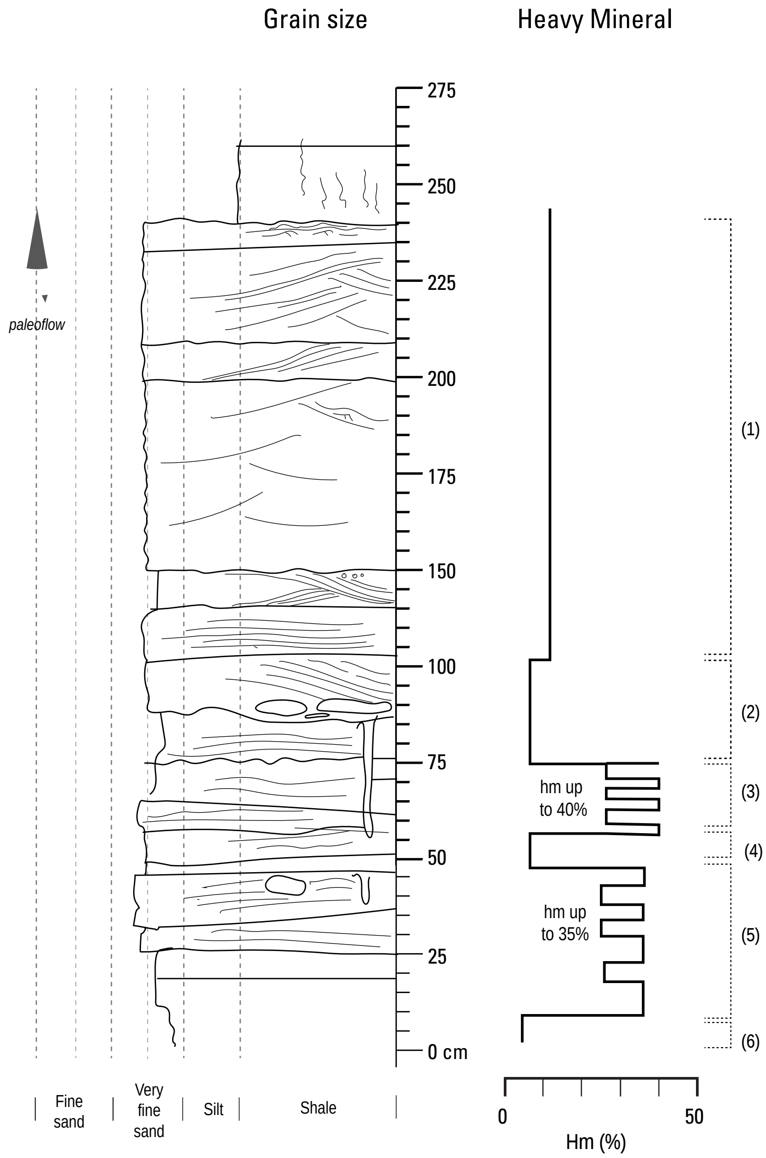


Figure – Generalized cross-section A-A' showing the location of Titanium Ridge to the southeast, Interstate 70 (I-70), and a beach placer trend along strike. Overlying surficial deposits not shown. Contacts and beach placers estimated from drilling information provided by others. m = meters, amsl = above mean sea level. The location of this cross section is shown on the "Cross Section Location Map" in this appendix.

Fox Hills Titanium Ridge TR-04

M. Dechesne, S. Keller

03/08/2019



Notes

(1) Gray resistant sandstone. Fine grained, very well sorted, angular to subangular, bedding at 0.5-2 cm with sigmoidal cross-bedding and wave ripples to top. Composition ~70% quartz, ~30% feldspar and other minerals (including ~10% heavy minerals). Munsell color 10YR 7/2 (light gray), strong effervescence, strong rock (ISRM), forms caprock here. Photos 278 and 279 in Appendix C.
Between 100 and 105 cm multidirectional (tidal) barforms with waveripples.

(2) Sandstone. Very fine-grained to fine-grained (vfU to fL), well sorted, subangular, bedding at 1-20 mm. Composition ~65% quartz, ~35% feldspar and other minerals (including <5% heavy minerals). Munsell color 10YR 7/1 (light gray), no effervescence. Contains oval-shaped light-brown sandstone rip-up clast ~60 cm long and ~30 cm thick. Small yellow iron oxide patches occur locally.

(3) Sandstone. Fine grained (fL to fU), well sorted, subangular to subrounded, laminated. Composition ~60% quartz, ~40% feldspar and other minerals (including ~20% heavy minerals). Dark-colored laminae are ~25% of interval thickness and contain up to 40% heavy minerals. No effervescence, very weak rock (ISRM).

(4) Sandstone. Fine grained (fL), very well sorted, subangular to subrounded, bedding mostly at ~20 mm. Composition ~75% quartz, ~25% feldspar and other minerals (including ~5% heavy minerals and <1% light green and pink accessory minerals). Munsell color 10YR 8/1 (white), no effervescence, very weak rock (ISRM).

(5) Sandstone. Fine grained (fU), very well sorted, subangular to subrounded, bedding at 3-23 mm. Composition ~70% quartz, ~30% feldspar and other minerals (including ~20% heavy minerals, and trace pink, light green, and orange accessory minerals). No effervescence, moderately indurated. Photo 277 in Appendix C.

(6) Sandstone. Fine grained (fU), very well sorted, subrounded to rounded, no visible bedding. Composition ~85% quartz, ~15% feldspar and other minerals (including <3% heavy minerals and possible trace epidote). No effervescence.

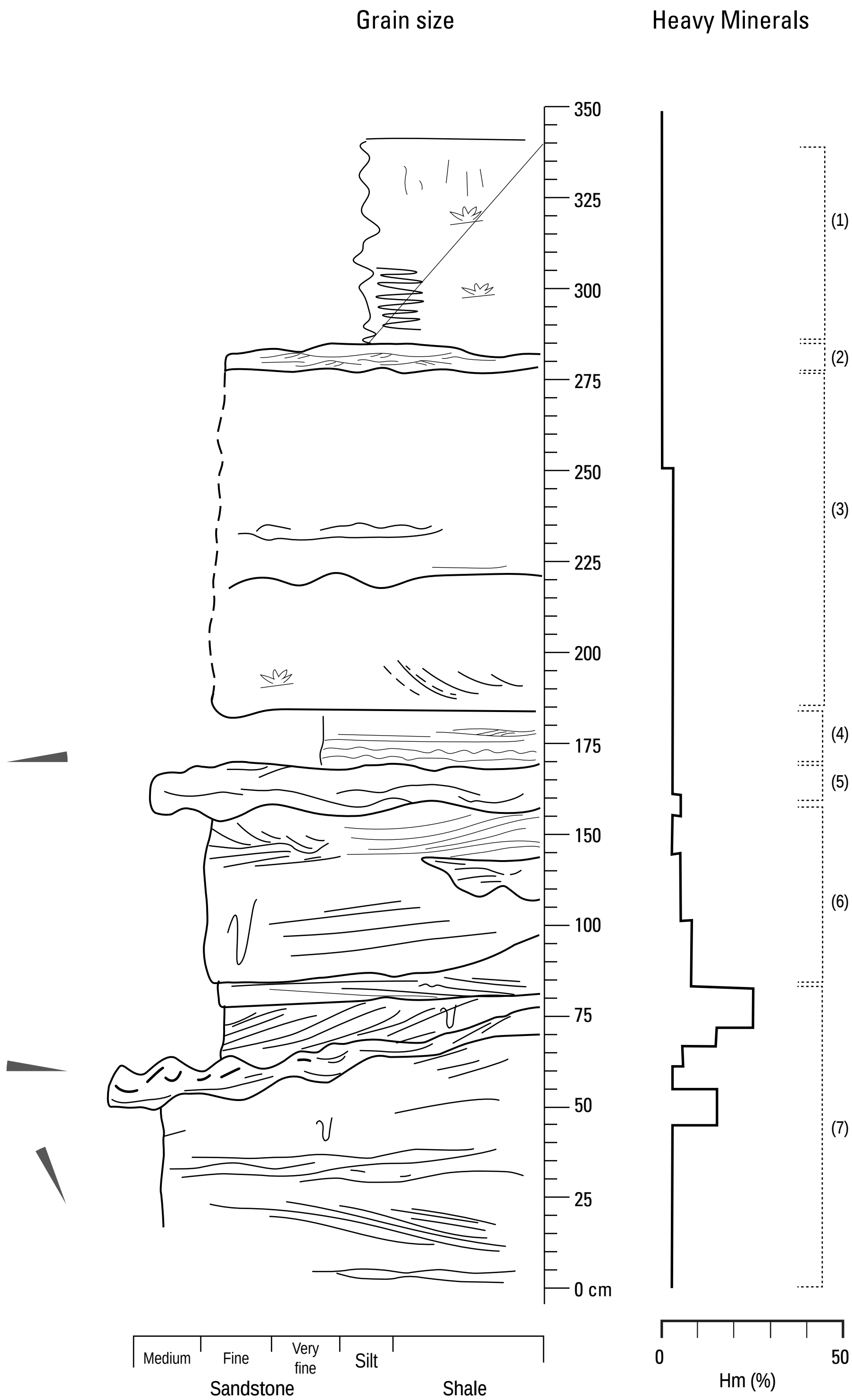
Measured Section Symbol Key

- paleoflow direction
- cover
- carbonaceous shale
- root casts
- horizontal burrows (*Ophiomorpha?*)
- *Ophiomorpha*
- *Skolithos*
- flaser bedding (isolated ripples in parallel laminated silt- and mudstone
- ripple marks
- wavy bedding to ripple marks
- parallel laminated sandstone
- sigmoidal cross beds (washover)
- herringbone cross-stratification
- cross stratification
- barforms (ripples on foresets)
- soft-sediment rip up clast
- erosional contact

Fox Hills Titanium Ridge TR-05

M. Dechesne, S. Keller

03/08/2019



Notes

(1) Dark-brown carbonaceous shale.
Laramie Formation.

(2) Gray resistant sandstone. Very fine grained (vfU), well sorted, subangular to subrounded, wave ripples. Composition ~75% quartz, ~25% feldspar and other minerals (including <5% heavy minerals). Munsell color 10YR 7/1 light gray), strong effervescence, strong rock (ISRM), well cemented.

(3) Sandstone. Fine grained (fU), well sorted. Composition ~80% quartz, ~20% feldspar and other minerals (including <5% heavy minerals). Munsell color 2.5Y 7/2 (light gray), no effervescence, very weak rock (ISRM).

(4) Gray resistant sandstone. Very fine grained to fine grained, well sorted, angular to subangular. Composition ~80% quartz, ~20% feldspar and other minerals (including ~5% heavy minerals). Munsell color 10YR 7/1 (light gray), very strong effervescence, strong rock (ISRM).

(5) Sandstone. Fine grained (fL), well sorted, subangular to rounded, wavy to small scours. Composition ~80% quartz and ~20% feldspar and other minerals (including <5% heavy minerals). Munsell color 5YR 6/1 (gray), no effervescence, moderately weak rock (ISRM), well cemented.

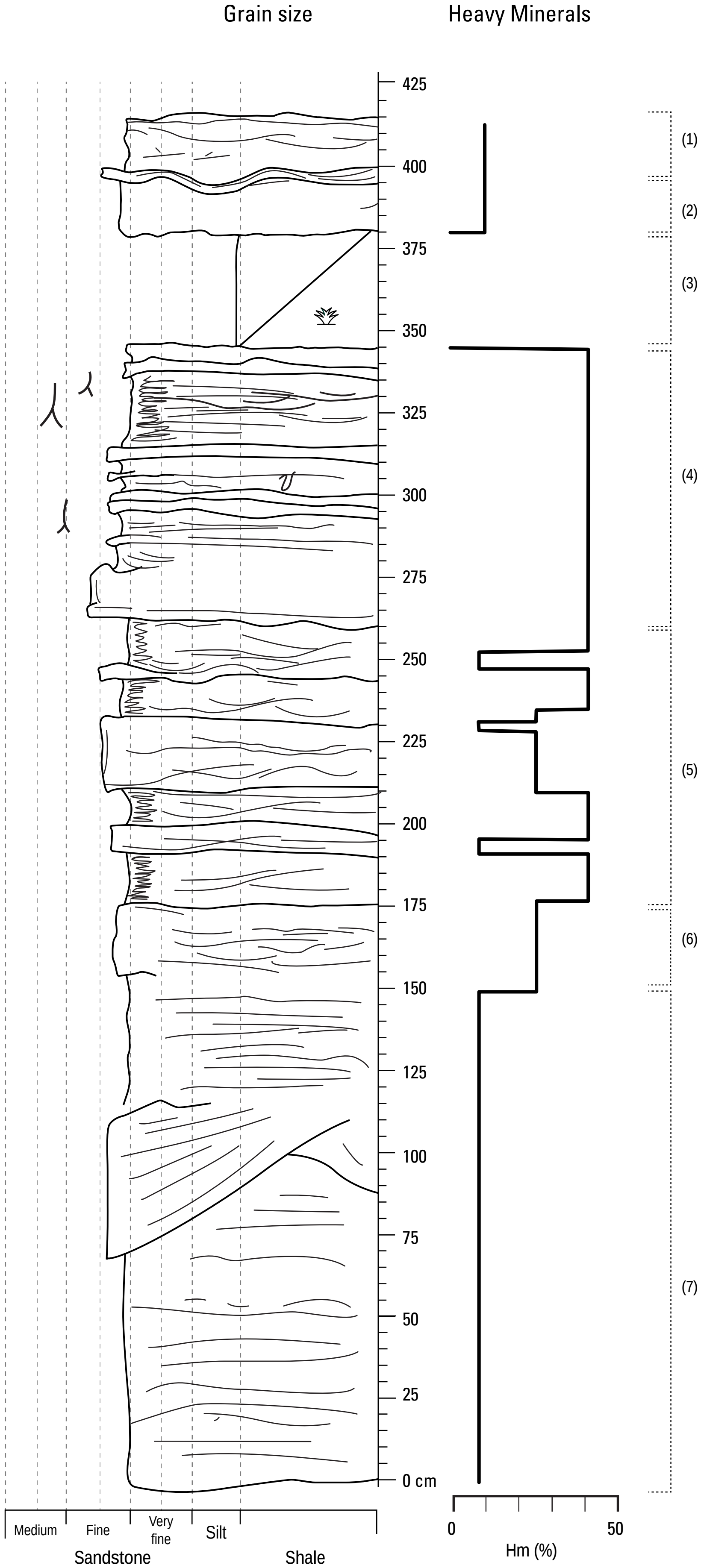
(6) Gray resistant sandstone. Very fine grained to fine grained, well sorted, subangular to subrounded, bedding at 2-4 cm, sigmoidal and herringbone cross-bedding at top of unit. Composition ~55% quartz and ~45% feldspar and other minerals (including ~15% heavy minerals). Munsell color 10YR 6/1 (gray), strong effervescence, well cemented. Photo 276 in Appendix C.

(7) Sandstone. Very fine grained to fine grained (vfL to fU), well sorted, angular to subangular, laminated (abundant heavy mineral laminae). Composition ~70% quartz and ~30% feldspar and other minerals (including <10% heavy minerals). Upper 3 cm of unit is very fine grained and ~80% quartz. Abundant heavy mineral laminae. Brown color, very weak rock (ISRM), soft-sediment rip-up clasts of fine-grained sandstone ~30 cm long and 5 cm thick. Photos 274, 275 in Appendix C.

Fox Hills Titanium Ridge TR-13

M. Dechesne, S. Keller, M. 'O Keeffe

04/18/2019



Notes

(1) Gray resistant sandstone. Fine grained to medium grained (fL to mU), moderately sorted, angular, bedded at mm's to cm's, abundant plant fragments, orange iron-oxide zone in lowest 5 cm; this interval forms cap rock here. Composition ~65% quartz and ~35% feldspar and other minerals (including only minor heavy minerals). Munsell color 10YR 7/1 (light gray).

(2) Sandstone. Fine grained to medium grained (fU to mL), well sorted, angular to subangular, massive. Composition ~75% quartz and 25% feldspar and other minerals (including <10% heavy minerals). Munsell color 10YR 8/1 (white), no effervescence, moderately weak rock (ISRM).

(3) Covered by colluvium.

(4) Sandstone. Fine grained, well sorted, angular to subangular, laminated. Heavy-mineral-rich laminae make up ~40% of interval thickness but are not concentrated in discrete layers; individual laminae can contain as much as ~40% heavy minerals. Munsell color 10YR 8/4 (pale brown), moderately weak rock (ISRM). Photo 372 in Appendix C.

(5) Sandstone. Very fine grained to fine grained (vfU to fL), well sorted, angular to subangular, laminated. Internal scours with 5-15 cm relief and cm-scale scours and discordances. Light-colored, heavy-mineral-poor l ayers (Munsell color 10YR 4/1, very pale brown with orange iron-oxide staining) alternate with dark-colored layers (10YR 4/1, dark gray) containing heavy-mineral-rich laminae. Light-colored layers are similar to overlying sandstone layer (at 67-152 bgs). Dark-colored layers are at ~165 cm, 205 cm, and 220 cm below ground surface (bgs). Composition of dark-colored layers is ~50% quartz and ~50% other minerals (including ~40% heavy minerals). Interval has no effervescence, moderately strong rock (ISRM). At ~ 6 m to southeast of this location, on southwest side of ridge, channel filling cross-cuts dark-colored layers. Photos 362-364, 366-368, 371 in Appendix C.

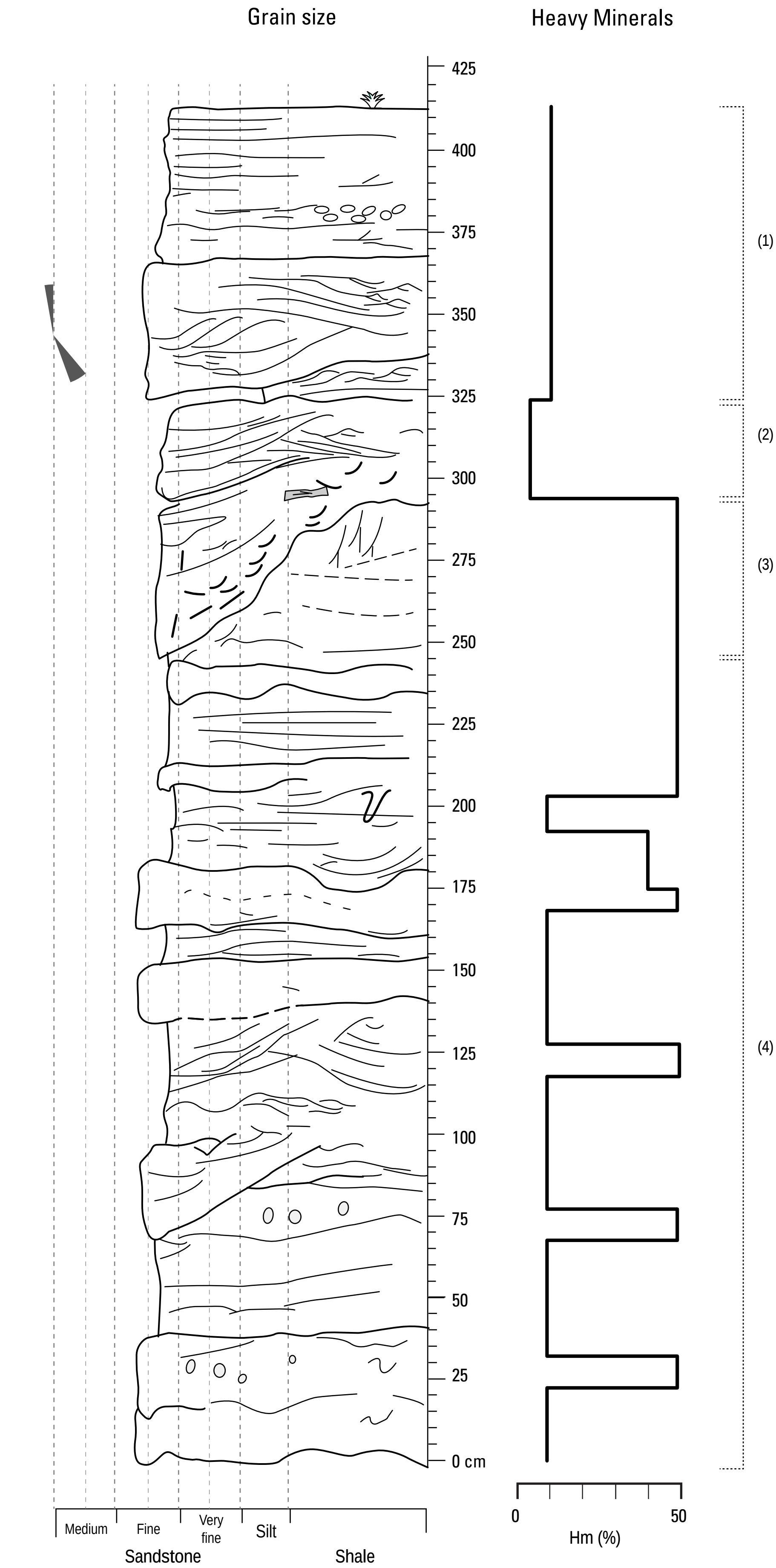
(6) Sandstone. Fine grained (fL to fU), well sorted, angular to subangular, bedding mm's to cm's; low-angle cross-bedding to parallel bedding is at cm scale. Composition ~65% quartz and ~35% feldspar and other minerals (including up to ~25% heavy minerals). Munsell color 10YR 7/3 (very pale brown), no effervescence, moderately strong rock (ISRM). Interval is possible transition between underlying, white, heavy-mineral-poor sandstone and overlying, gray and orange, heavy-mineral-rich sandstone. Photo 370 in Appendix C.

(7) Sandstone. Fine grained, well sorted, angular to subangular, parallel bedded; bedded at 2-10 cm in lower part and from laminae to mm's in upper part. Prominent scour filling in middle portion, 150 cm wide by 50 cm deep. Composition ~80% quartz and ~20% feldspar and other minerals (including ~8% heavy minerals). Munsell color 10YR 8/2 (white), moderately strong rock (ISRM), weathers massive, has orange iron-oxide staining in upper part. Photos 362, 364, 365 in Appendix C.

Fox Hills Titanium Ridge TR-14

M. Dechesne, S. Keller

04/18/2019



(1) Gray resistant sandstone, upper part. Fine grained (fL to fU), well sorted, angular to subangular, partly finely laminated and partly bedded at 1-5 cm. Bedding-parallel burrows 0.6 cm diameter, Ophiomorpha(?), at 25 cm below ground surface (bgs). Cross-bedding in lower half of interval is 80-100 cm wide and 20 cm thick. Flaser bedding at base of nterval. Composition ~80% quartz and ~20% feldspar and other minerals (including ~10% heavy minerals). Munsell color 10YR 7/2 (light gray), visible carbonate cement, strong effervescence, strong rock (ISRM). Upper part of interval distinct from the lower part (90-120 cm), in that it is thicker bedded, more indurated, and lacks oxidized zones and rip-up clasts. Photos 384, 385 Appendix C.

(2) Gray resistant sandstone, lower part. Fine grained to medium grained (fL to mU), moderately sorted, angular, bedded at mm's to cm's. Multi-directional sigmoidal cross-bedding is 80-100 cm wide and 20 cm thick, possibly caused by washover. Base of interval is 45-cm-deep erosional scour with root casts. Scour includes wood fragments 2-3 cm, coal rip-up clasts 0.7 cm, and rip-up clasts of orange sandstone up to 10 cm x 20 cm. Composition ~65% quartz and ~35% feldspar and other minerals (including only minor heavy minerals). Munsell color 10YR 7/1 (light gray), with 2-4 cm oxidized zone 7.5Y 5/6 (strong brown) above erosion surface on underlying gray sandstone; other oxidized zones present Photos 378, 380 in Appendix C.

(3) Sandstone. Same as underlying interval (at 165-415 cm bgs), but with common internal scouring and irregular, subvertical, "wiggly" features, possibly root casts, obscuring bedding in an oval-shaped zone ~0.5 m thick and ~1 m wide. Photo 383 in Appendix C.

(4) Sandstone. Fine grained (fL to fU), well sorted, subangular to subrounded, bedded mostly at mm's, wavy laminae in 25-cm bands in lower part of interval. Composition ~75% quartz and ~25% feldspar and other minerals (including ~15% heavy minerals). Munsell color 10YR 7/2 (light gray), no effervescence, moderately weak rock (ISRM). Interval has four gray layers fairly evenly spaced vertically. These consist of 30-50% dark laminae, and dark laminae contain 50-75% heavy minerals. Gray layers alternate with white, heavy-mineral-poor sandstone layers and orange iron-oxide zones. Interval contains cross-cutting channel fill or furrow feature. Photos 373-377, 379 in Appendix C.

Stratigraphic section field notes at select locations (see Figure 15). See Table 6 for handheld XRF sample screening results. See photo log in this appendix for the photos listed in the description.

Centimeters (below ground surface)	Feet (below ground surface)	Lithology	Description
TR-04 (date: 3-7-19)			
0-90	0-3.5	sandstone	Interval is same as underlying interval at 90-134 cm, but is covered with colluvium except for outcrop at ground surface (at top of hill).
90-134	3.5-5.3	gray resistant sandstone	Gray resistant sandstone (informal field term for this lithology) is fine-grained (fL), very well sorted, and angular to subangular. Composition is ~70% quartz, ~30% feldspar and other minerals (including ~10% heavy-minerals). Munsell color is 10YR 7/2 (light gray); has strong effervescence and is strong rock (ISRM). Photos 278, 279.
134-165	5.3-6.5	sandstone	Sandstone is very fine-grained to fine-grained (vfU to fL), well sorted, and subangular, with bedding at 1-20 mm. Composition is ~65% quartz, ~35% feldspar and other minerals (including <5% heavy-minerals). Munsell color is 10YR 7/1 (light gray); no effervescence. Oval-shaped light brown sandstone rip-up clast is ~60 cm long and ~30 cm thick. Small yellow iron-oxide patches occur locally.
165-178	6.5-7.0	sandstone	Sandstone is fine-grained (fL to fU), well sorted, and subangular to subrounded. Composition is ~60% quartz, ~40% feldspar and other minerals (including ~20% heavy-minerals). Dark-colored laminae are ~25% of interval thickness and contain up to 40% heavy-minerals. Very weak rock (ISRM), no effervescence.
178-192	7.0-7.6	sandstone	Sandstone is fine-grained (fL), very well sorted, subangular to sunrounded, and bedded mostly at ~20 mm. Composition is ~75% quartz, ~25% feldspar and other minerals (including ~5% heavy-minerals and <1% light green and pink accessory minerals). Munsell color is 10YR 8/1 (white); no effervescence, very weak rock (ISRM).
192-232	7.6-9.2	sandstone	Sandstone is fine-grained (fU), very well sorted, subangular to subrounded, and bedded at 3-23 mm. Composition is ~70% quartz, ~30% feldspar and other minerals (including ~20% heavy-minerals, and trace pink, light green, and orange accessory minerals). No effervescence, moderately indurated. Photo 277; sample TR-04REF1.
232-240	9.2-9.5	sandstone	Sandstone is fine-grained (fU), very well sorted, subrounded to rounded, with no visible bedding. Composition is ~85% quartz, ~15% feldspar and other minerals (including <3% heavy-minerals and possible trace epidote). No effervescence.
TR-05 (3-7-19)			
0-90	0.3.5	Laramie Formation	Laramie Formation, not described.
90-100	3.5-3.9	gray resistant sandstone	Gray resistant sandstone is very fine-grained (vfU), well sorted, subangular to subrounded, and displays wave ripples in side view. Composition is ~75% quartz, ~25% feldspar and other minerals (including <5% heavy-minerals). Munsell color is 10YR 7/1 (light gray); strong effervescence, strong rock (ISRM).
100-196	3.9-7.7	sandstone	Sandstone is mostly covered by colluvium, fine-grained (fU), well sorted. Composition is ~80% quartz, ~20% feldspar and other minerals (including <5% heavy-minerals). Munsell color is 2.5Y 7/2 (light gray); no effervescence, very weak rock (ISRM).
196-214	7.7-8.4	gray resistant sandstone	Gray resistant sandstone is very fine-grained to fine-grained, well sorted, and subangular to angular. Composition is ~80% quartz, ~20% feldspar and other minerals (including ~5% heavy-minerals). Munsell color is 10YR 7/1 (light gray); very strong effervescence; strong rock (ISRM).
214-226	8.4-8.9	sandstone	Sandstone is fine-grained (fL), well sorted, and subangular to rounded. Composition is ~80% quartz and ~20% feldspar and other minerals (including <5% heavy-minerals). Munsell color is 5YR 6/1 (gray); no effervescence, moderately weak rock (ISRM).
226-246	8.9-9.7	covered	Covered by colluvium.

Lower and upper case letters to refer to sand sizes. Here, vc stands for very coarse, c for coarse, m for medium, f for fine and vf for very fine; L stands for the lower limit and U for the upper limit of these grain sizes. For example, vcU is the upper limit of very coarse sand; vfL is the lower limit of very fine sand (description from www.cgsmule.com). bgs – below ground surface, cm – centimeter, cms – centimeters, mm – millimeter, mms – millimeters, m – meter, ft – feet, ISRM – International Society for Rock Mechanics and Rock Engineering.

Stratigraphic section field notes at select locations (see Figure 15). See Table 6 for handheld XRF sample screening results. See photo log in this appendix for the photos listed in the description.

246-264	9.7-10.4	gray resistant sandstone	Gray resistant sandstone is very fine-grained to fine-grained, well sorted, subangular to subrounded, and with sigmoidal cross-bedding. Composition is ~55% quartz and ~45% feldspar and other minerals (including ~15% heavy-minerals). Munsell color is 10YR 6/1 (gray); strong effervescence. Photo 276.
264-305	10.4-12.0	sandstone	Sandstone is very fine-grained to fine-grained (vfL to fU), well sorted, and angular to subangular. Composition is ~70% quartz and ~30% feldspar and other minerals (including <10% heavy-minerals). Upper 3 cm of unit is very fine-grained and ~80% quartz. Brown, very weak rock (ISRM), with fine-grained sandstone rip-up clast ~30 cm long and 5 cm thick. Photos 274, 275.
305-310	12.0-12.2	sandstone	Sandstone is fine-grained, (fL), well sorted, and angular to subangular. Munsell color is 10YR 6/4 (black). Composition is ~55% quartz and ~45% feldspar and other minerals (including ~25% heavy-minerals). No effervescence, extremely weak rock (ISRM). Photos 272, 273.
310-318	12.2-12.5	sandstone	Sandstone is fine-grained (fL to fU), well sorted, subangular to subrounded, bedded at 1-3 mm, and extremely weak rock (ISRM). Composition is ~60% quartz and ~40% feldspar and other minerals (including ~15% heavy-minerals and possible trace epidote). Unit contains minor black, heavy-mineral-rich laminae. Munsell color is 10YR 6/4 (black). Photo 273.
318-324	12.5-12.7	sandstone	Sandstone is very fine-grained to fine-grained, well sorted, subangular to angular, and has *Ophiomorpha* burrows. Composition is ~70% quartz and ~30% feldspar and other minerals (including ~5% heavy-minerals). No effervescence, moderately indurated. Photo 272, sample TR-05REF1.
324-333	12.7-13.1	sandstone	Sandstone is fine-grained to medium grained (fU to mL), well sorted, and angular to subangular. Composition is ~65% quartz and ~35% feldspar and other minerals (including ~10% heavy-minerals). No effervescence, extremely weak rock (ISRM).
333-358	13.1-14.1	sandstone	Sandstone is very fine-grained to fine-grained (vfL to fU), well sorted, and subangular. Upper contact of this interval is an erosional surface. Composition is ~70% quartz and ~30% feldspar and other minerals (including ~3% heavy-minerals). No effervescence, extremely weak rock (ISRM). Photo 271.
TR-07 (3-8-19)			
0-60	0-2.4	gray resistant sandstone	Gray resistant sandstone is very similar to gray resistant sandstone at TR-04 and TR-05: fine-grained, strong rock (ISRM), light gray, and bedding at 1-4 cm. Interval has prominent sigmoidal cross-bedding with height ~30 cm and wavelength ~3 m. Also, flat outcrop at top of interval has wave ripples with height ~1 cm and wavelength ~10 cm; wave crests oriented azimuth 185°. Photos 291-297.
60-605	2.4-23.5	covered	Covered with colluvium.
605-632	23.5-24.6	sandstone	Sandstone is fine-grained (fL to fU) and well sorted, has few heavy-minerals, and has orange iron-oxide zones. There are rip-up clasts of black carbonaceous laminated silt, and lenses of brown carbonaceous silty clay or clayey silt, and of off-white, calcareous, moderately strong rock (ISRM). Photo 346, sample TR-07REF4.
632-650	24.6-25.3	sandstone and siltstone	Interval consists of fine-grained (fL) grayish-green and (oxidized) orange sandstone interbedded with carbonaceous, micaceous siltstone. Both lithologies have little or no heavy-mineral content, and are extremely weak rock (ISRM). Base of interval is 9 cm of very fine-grained to fine-grained (vfU to fL), well sorted, angular to subangular sandstone, overlain by 3 cm of micaceous, carbonaceous clayey silt or silty clay with abundant dark laminae (with no heavy-minerals). Photos 344, 345; samples TR-07REF3 and TR-07REF3A.
650-730	25.3-28.5	sandstone	Sandstone is fine-grained (fL to fU), well sorted, and massive, with ~7% heavy-minerals. Sample TR-07REF1.
TR-08 (3-8-19)			
0-60	0-2.4	gray resistant sandstone	Continuation of caprock at TR-07, 0-60 cm.

Lower and upper case letters to refer to sand sizes. Here, vc stands for very coarse, c for coarse, m for medium, f for fine and vf for very fine; L stands for the lower limit and U for the upper limit of these grain sizes. For example, vcU is the upper limit of very coarse sand; vfL is the lower limit of very fine sand (description from www.cgsmule.com). bgs – below ground surface, cm – centimeter, cms – centimeters, mm – millimeter, mms – millimeters, m – meter, ft – feet, ISRM – International Society for Rock Mechanics and Rock Engineering.

Stratigraphic section field notes at select locations (see Figure 15). See Table 6 for handheld XRF sample screening results. See photo log in this appendix for the photos listed in the description.

60-440	2.4-17.4	covered	Covered by colluvium.
440-480	17.4-19.0	sandstone	Sandstone has salt-and-pepper appearance caused by ~7% disseminated heavy-minerals; fine-grained (fU), angular, very weak rock (ISRM), off-white. Upper 20 cm has flat rip-up clasts of white, speckled clay or silt. Photos 301, 302; samples TR-08REF2 and TR-08REF3.
480-500	19.0-19.8	sandstone	Sandstone is very fine-grained to fine-grained, with ~20% of thickness being dark laminae having up to 30% heavy-minerals. Sandstone outside laminae is ~5% heavy-minerals. Interval is cross-laminated with some laminae orange-stained. Photos 302, 303; sample TR-08REF1.
500-640	19.8-25.3	sandstone	Sandstone is very fine-grained, light gray, massive, and very weak rock (ISRM). Photos 298, 299.
TR-09 (3-8-19)			
0-60	0-2.4	gray resistant sandstone	Continuation of caprock at TR-07, 0-60 cm and TR-08, 0-60 cm. Has erosional contact with underlying sandstone interval.
60-90	2.4-3.6	sandstone	Isolated pod of salt-and-pepper sandstone of TR-08, 160-200 cm. Pod is ~60 cm long and ~30 cm thick. Photos 305-307.
90-230	3.6-9.1	sandstone	Sandstone is very fine-grained, well sorted, and massive. Photo 304.
TR-10 (4-4-19)			
0-55	0-2.2	gray resistant sandstone	Gray resistant sandstone caprock is similar to that north of I-70: fine-grained to medium grained (fU to mL), moderately sorted, and subangular to subrounded. Composition is ~70% quartz and 30% feldspar and other minerals (including ~3% heavy-minerals). Munsell color 10YR 6/2 (light brownish gray); strong effervescence, strong rock (ISRM). Rock has abundant secondary carbonate coatings and fracture fillings; purple-brown and orange spherical concretions 3-30 mm in diameter; and cross-bedding and ripple marks. Photos 329-331.
55-177	2.2-6.0	sandstone	Sandstone is fine-grained (fL to fU), well sorted, and subangular to subrounded. Composition is ~70% quartz and 30% feldspar and other minerals (including ~15% heavy-minerals in most of interval). Upper 15 cm of interval has ~40% heavy-minerals and lower part has ~20%. Munsell color is 10YR 5/6 (yellowish brown). Interval is bedded from 2 mm to 10 cm, with some contorted bedding. No effervescence, extremely weak rock (ISRM), some orange iron-oxide staining near top. Photos 326-328; sample TR10-XRF.
177-244	6.0-8.6	sandstone	Sandstone is fine-grained (fU to mL), moderately sorted, and angular to subangular. Composition is ~80% quartz and 20% feldspar and other minerals (including <10% heavy-minerals). Munsell color is 2.5Y 7/2 (light gray) with iron-oxide-stained bands 7.5YR 7/8 (reddish yellow). Interval has no heavy-mineral laminae; no effervescence, moderately weak rock (ISRM). Photo 325.
244-299	8.6-10.8	sandstone	Sandstone is fine-grained to medium grained (fL to fU), moderately sorted, and angular to subangular. Composition is ~70% quartz and 30% feldspar and other minerals (including <5% heavy-minerals). Munsell color is 2.5Y 6/2 (light brownish gray). There is no sharp contact with overlying interval, but markedly less iron-oxide banding in overlying interval. No effervescence, moderately weak rock (ISRM). Photo 324.
TR-11 (4-4-19)			
0-49	0-1.9	sandstone	Sandstone same as underlying sandstone, but strong rock (ISRM) and dominated by deep orange-brown, purple-black, and purple-brown iron-oxide and manganese oxide staining. Photos 338, 339, 341.
49-122	1.9-4.8	sandstone	Sandstone is fine-grained (fL to fU), well sorted, and angular to subangular. Composition is ~80% quartz and 20% feldspar and other minerals (including <3% heavy-minerals). Munsell color is 10YR 8/2 (white). Interval has massive weathering, bedding at several cm, no heavy-mineral laminae, and is moderately strong rock (ISRM). Photos 338, 340, 341; sample TR-11REF.

Lower and upper case letters to refer to sand sizes. Here, vc stands for very coarse, c for coarse, m for medium, f for fine and vf for very fine; L stands for the lower limit and U for the upper limit of these grain sizes. For example, vcU is the upper limit of very coarse sand; vfL is the lower limit of very fine sand (description from www.cgsmule.com). bgs – below ground surface, cm – centimeter, cms – centimeters, mm – millimeter, mms – millimeters, m – meter, ft – feet, ISRM – International Society for Rock Mechanics and Rock Engineering.

Stratigraphic section field notes at select locations (see Figure 15). See Table 6 for handheld XRF sample screening results. See photo log in this appendix for the photos listed in the description.

			NOTE: The above-described white and orange sandstone (0-122 cm) is juxtaposed with and is at the same elevation as an adjacent outcrop of gray resistant sandstone (the same caprock as at TR-10 and north of I-70). This is shown in photos 332-334, 338, 340, and 341. The white and orange sandstone filling a scour pocket in the gray caprock is shown in photos 335-337 and 339. The gray sandstone caprock adjacent to and east of the white and orange sandstone is shown in photos 342 and 343. The white and orange sandstone apparently fills a channel incised in gray resistant sandstone caprock. The scour pocket is the only place at the outcrop where the contact between the orange and white sandstone (presumably older) and the gray resistant sandstone (presumably younger) is exposed.
TR-01 (4-5-19)			
0-21	0-0.8	sandstone	Sandstone is fine-grained (fU), well sorted, and subrounded to rounded. Composition is ~80% quartz and 20% feldspar and other minerals (including <10% disseminated heavy-minerals). Munsell color is 10YR 4/4 (dark yellowish brown); no effervescence, extremely weak rock (ISRM), no heavy-mineral laminae. Brown color is probably due to organic matter from overlying soil. Photo 350.
21-122	0.8-4.8	sandstone	Sandstone is fine-grained to medium grained (fU to mL), well sorted, and subangular to subrounded. Composition is ~75% quartz and 25% feldspar and other minerals (including <10% disseminated heavy-minerals). Munsell color is 2.5Y 7/4 (pale yellow) with iron-oxide streaks 7.5Y 6/8 (reddish yellow). Bedding is from mms to 10 cm with some possible cross-bedding; no effervescence. Photos 351, 353, 354.
122-143	4.8-5.6	sandstone	Sandstone is very fine-grained to medium grained (vfU to mL), moderately sorted, and subangular to subrounded. Composition is ~75% quartz and 25% feldspar and other minerals (including <10% disseminated heavy-minerals). Munsell color is 2.5Y 6/4 (light yellowish brown). Interval has no effervescence, no heavy-mineral laminae, a few iron-oxide streaks. Photo 352.
TR-12 (4-5-19)			
0-195	0.7.7	sandstone	Sandstone is fine-grained (fL to fU), well sorted, angular to subangular. Composition is ~75% quartz and 25% feldspar and other minerals (including <3% disseminated heavy-minerals). Munsell color is 2.5Y 7/6 (yellow) with prominent iron-oxide and manganese-oxide staining in ochre, rust red, purple, and purple-brown. This interval is strong rock (ISRM), bedding is mm- to cm-scale, and has no effervescence. Photos 356, 357, 361; sample TR-12REF1.
195-305	7.7-12.0	sandstone	Sandstone is fine-grained (fL to fU), well sorted, and angular to subangular. Composition is ~85% quartz and 15% feldspar and other minerals (including trace disseminated heavy-minerals). Munsell color is 5Y 7/3 (pale yellow). Interval is moderately strong rock (ISRM), has no effervescence and no heavy-mineral laminae. Bedding is at mms to cms, and weathered face suggests cross-bedding. Photos 356-361, sample TR-12REF2.
TR-13 (4-18-19)			
0-17	0-0.7	gray resistant sandstone	Gray resistant sandstone is caprock, and contains plant stems and an oxidized zone in lowest 5 cm (see TR-14, 90-120 cm for description).
17-32	0.7-1.3	sandstone	Sandstone is fine-grained to medium grained (fU to mL), well sorted, angular to subangular, and massive. Composition is ~75% quartz and 25% feldspar and other minerals (including <10% heavy-minerals). Munsell color is 10YR 8/1 (white); no effervescence, moderately weak rock (ISRM).
32-67	1.3-2.7	covered	Covered with colluvium.
67-152	2.7-6.1	sandstone	Sandstone is fine-grained, well sorted, angular to subangular, and bedded at mms to cms. Heavy-mineral-rich laminae make up ~40% of interval thickness but are not concentrated in a horizon; individual laminae can contain as much as ~40% heavy-minerals. Munsell color is 10YR 8/4 (pale brown); moderately weak rock (ISRM). Photo 372, sample TR-13REF2

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Stratigraphic section field notes at select locations (see Figure 15). See Table 6 for handheld XRF sample screening results. See photo log in this appendix for the photos listed in the description.

152-237	6.1-9.5	sandstone	Sandstone is very fine-grained to fine-grained (vfU to fL), well sorted, angular to subangular, and bedded at mms. Light-colored, heavy-mineral-poor horizons (10YR 4/1, very pale brown with orange iron-oxide staining) alternate with dark-colored horizons (10YR 4/1, dark gray) of heavy-mineral-rich laminae. Dark-colored horizons are at 160-175 cm, 195-215 cm, and 220-237 cm. Light-colored horizons are similar to 67-152 cm. Composition of dark-colored horizons is ~50% quartz and ~50% other minerals (including ~40% heavy-minerals). Interval has no effervescence and overall is moderately strong rock (ISRM). At ~ 6 m to southeast, on southwestern side of ridge, channel filling cross-cuts dark-colored horizons (photo 369). Photos 362-364, 366-368, 371; sample TR-13REF1.
237-262	9.5-10.5	sandstone	Sandstone is fine-grained (fL to fU), well sorted, angular to subangular, and bedded up to cms. Composition is ~65% quartz and ~35% feldspar and other minerals (including up to ~25% heavy-minerals). Munsell color is 10YR 7/3 (very pale brown); no effervescence, moderately strong rock (ISRM). Interval is possible transition between underlying, white, heavy-mineral-poor sandstone and overlying, gray and orange, heavy-mineral-rich sandstone. Photo 370.
262-412	10.5-16.4	sandstone	Sandstone is fine-grained, well sorted, angular to subangular, and bedded up to 8 cm in lower part, at mms in upper part. Composition is ~80% quartz and ~20% feldspar and other minerals (including ~8% heavy-minerals). Munsell color is 10YR 8/2 (white). Interval is moderately strong rock (ISRM), weathers massive, has orange iron-oxide staining in upper part, and channel filling or furrow in lower part (photo 365). Photos 362, 364, 365.
TR-14 (4-18-19)			
0-90	0-3.5	gray resistant sandstone	Upper part of gray resistant sandstone is fine-grained (fL to fU), well sorted, subangular to subrounded, and bedded at 1-3 cm. Composition is ~80% quartz and ~20% feldspar and other minerals (including ~10% heavy-minerals). Munsell color is 10YR 7/2 (light gray). Interval has visible carbonate cement, strong effervescence, and is strong rock (ISRM). Distinctive undulating sigmoidal cross-bedding resembles megaripples, but really is a different bedform possibly caused by storm-related washover. Height of undulations is 10-20 cm, wavelength is 1-2 m. This upper part of the gray resistant sandstone is distinct from the lower part (90-120 cm), in that it is thicker bedded, more indurated, and lacks oxidized zones and rip-up clasts. Photos 384, 385.
90-120	3.5-4.7	gray resistant sandstone	Lower part of gray resistant sandstone is fine-grained to medium grained (fL to mU), moderately sorted, angular, and bedded at mms to cms. Composition is ~65% quartz and ~35% feldspar and other minerals (including only minor heavy-minerals). Munsell color is 10YR 7/1 (light gray), with 2-4 cm oxidized zone 7.5Y 5/6 (strong brown) lying on erosional surface on underlying gray resistant sandstone, as well as other oxidized zones. Interval contains root fragments 2-3 cm in diameter, rare coal fragments 0.7 cm in diameter in oxidized zone, and rip-up clasts of orange sandstone up to 10 cm x 20 cm. Photos 378, 380; photo 9991.
120-165	4.7-6.5	sandstone	Same as underlying interval at 165-415 cm, but with irregular, subvertical, "wiggly" features, possibly root fillings, obscuring bedding in an oval-shaped zone ~0.5 m thick and ~1 m long. Photo 383; photos 9985, 9989, 9991.
165-415	6.5-16.3	sandstone	Sandstone is fine-grained (fL to fU), well sorted, subangular to subrounded, and bedded mostly at mms. Composition is ~75% quartz and ~25% feldspar and other minerals (including ~15% heavy-minerals). Munsell color is 10YR 7/2 (light gray); no effervescence, moderately weak rock (ISRM). Interval has four gray horizons in which dark-colored, heavy-mineral-rich laminae are concentrated. These gray horizons alternate with white, heavy-mineral-poor sandstone and orange oxidized zones. Gray horizons consist of 30-50% dark laminae, and individual laminae are 50-75% heavy-minerals. Interval contains cross-cutting channel fill or furrow feature (photos 381, 382). Photos 373-377, 379; sample TR-14REF1; photos 0017, 9983, 9984.

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Stratigraphic section field notes at select locations (see Figure 15). See Table 6 for handheld XRF sample screening results. See photo log in this appendix for the photos listed in the description.

TR-15 (4-26-19)			
0-115	0-4.5	sandstone	Sandstone is very fine-grained to fine-grained (vfU to fL), well sorted, subangular to subrounded, and bedded at mms. Composition is ~85% quartz and ~15% feldspar and other minerals (including <5% heavy-minerals). Munsell color is 10YR 7/2 (light gray). Interval has no effervescence, has no heavy-mineral-rich laminae, is extremely weak rock (ISRM), has minor orange iron-oxide staining, and has faint cross-bedding. Exposure is poor.
115-149	4.5-5.8	shale or mudstone	Shale or mudstone, possibly uppermost transition member (Kpt) of Pierre Shale. Interval is Munsell color 10YR 5/1 (gray), is fissile in part, is extremely weak rock (ISRM), and has no effervescence. Basal 12 cm has small lenses of well sorted fine-grained sandstone, well indurated with some iron-oxide staining. Photo 401, sample TR-15REF2.
149-250	5.8-9.8	sandstone	Sandstone also possibly is Kpt, and is fine-grained (fL to fU), well sorted, angular to subangular, and bedded at mms to cms. Composition is ~80% quartz and ~20% feldspar and other minerals (including <5% heavy-minerals). Munsell color is 10YR 8/4 (very pale brown). Interval has no effervescence and is very weak rock (ISRM). Interval has cross-bedding and small furrow fillings; possible root casts or small burrow fillings, 3-5 cm in diameter and 3-10 cm high; and contains an erosional surface with lithic fragments 1 cm in diameter. Photos 395, 396.
250-350	9.8-13.7	sandstone	Sandstone also possibly is Kpt, and is well sorted, angular to subangular, and bedded at mms to cms. Composition is ~80% quartz and ~20% feldspar and other minerals (including <5% heavy-minerals). Munsell color is 10YR 8/2 (white) with orange iron-oxidized zones in some beds and laminae. Interval has no heavy-mineral-rich laminae, has no effervescence, and is very weak rock (ISRM). Interval has cross-bedding, furrow fillings, and orange-brown iron-oxidized concretions or burrow fillings 3-4 cm in diameter. Photos 396-400, sample TR-15REF1.
			Note: Downslope from above outcrop there is an additional ~25 ft of interbedded sandstone and shale; not described, but looks like Pierre Shale. Photo 402.
TR-16 (4-26-19)			
0-220	0-8.7	sandstone	Sandstone is very similar to sandstone of 220-247 cm, but impregnated with orange iron-oxide minerals and with some purple manganese-oxide staining on weathered surfaces (strong rock, ISRM). Interval has abundant burrow fillings 1-3 cm in diameter and up to 15 cm long. Interval weathers to jagged forms with abundant cavities. Photos 403, 405.
220-247	8.7-9.8	sandstone	This sandstone interval is possibly a transition zone from an underlying light-colored, moderately indurated interval to an overlying orange and purple, heavily impregnated and indurated interval. Very similar to underlying sandstone but lacks concretions and burrow fillings.
247-366	9.8-14.5	sandstone	Sandstone is fine-grained (fL to fU), well sorted, subangular to subrounded, and bedded at mms. Composition is ~75% quartz and ~25% feldspar and other minerals (including <10% heavy-minerals). Munsell color is 10YR 8/4 (very pale brown). Interval has no effervescence, is moderately strong rock (ISRM), and has cross-bedding and burrow fillings. Lower 60 cm has abundant circular to ovoid possible burrow fillings, 2-4 cm in diameter, and are orange iron-oxide and purple manganese-oxide stained at base of interval. Photos 403, 404; sample TR-16REF1.
TR-17 (4-26-19)			
0-49	0-1.9	gray resistant sandstone	Upper layer of gray resistant sandstone is fine-grained (fL to fU), well sorted, subangular to subrounded, and bedded at 1-5 cm. Composition is ~75% quartz and ~25% feldspar and other minerals (including <10% heavy-minerals). Munsell color is 10YR 7/1 (light gray); strong effervescence, strong rock (ISRM). Exposure is poor. Photos 406, 408.
49-67	1.9-2.6	sandstone	Sandstone is fine-grained to medium grained (fL to mL), moderately sorted, subangular to subrounded, and bedded at mms. Composition is ~75% quartz and

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			~25% feldspar and other minerals (including <10% heavy-minerals). Munsell color is 10YR 7/1 (light gray). Interval has no effervescence, is cross-bedded, has salt-and-pepper appearance caused by disseminated heavy-minerals, and has a few faint heavy-mineral-rich laminae. Photo 408, sample TR-17REF3.
67-79	2.6-3.1	sandstone	Lower layer of gray resistant sandstone is fine-grained (fL to fU), well sorted, and subangular to subrounded. Composition is ~75% quartz and ~25% feldspar and other minerals (including <10% heavy-minerals). Munsell color is 10YR 7/3 (very pale brown). Interval is strong effervescent, has visible carbonate cement, is strong rock (ISRM), and has minor iron-oxide staining.
79-82	3.1-3.2	sandstone	Sandstone is fine-grained to medium grained (fL to mL), moderately sorted, angular to subangular, and bedded at mms. Munsell color is 7.5 YR 4/3 (dark brown). Interval has no effervescence, is extremely weak rock (ISRM), and has abundant brown carbonaceous, micaceous laminae with minor orange-brown iron-oxide staining. Sample TR-17REF2.
82-509	3.2-20.0	sandstone	Sandstone is fine-grained (fL to fU), well sorted, angular to subangular, and faintly bedded at mms. Composition is ~75% quartz and ~25% feldspar and other minerals (including 10% heavy-minerals). Munsell color is 10YR 7/2 (light gray). Interval has no effervescence, is extremely weak rock (ISRM), and has salt-and-pepper appearance caused by disseminated heavy-minerals. There are rare orange iron-oxide patches, but otherwise interval is uniform from top to bottom. Photos 406, 407; sample TR-17REF1.

NOTES: Sections and notes by S. Keller. Photos referred to here are available upon request.

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Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo278

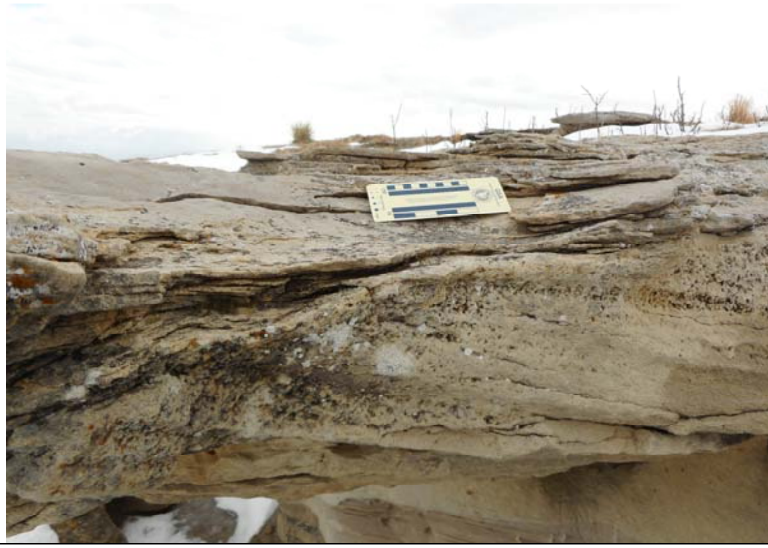


Photo279

Photo277

Photo276

Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo274

Photo275

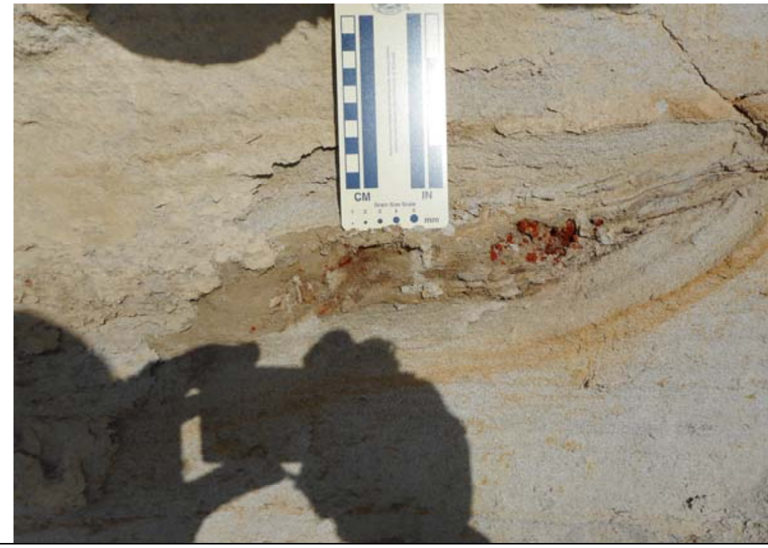


Photo272/273

Photo271

Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo291 – scale is extended to 1.2 m (4 ft).

Photo292 – scale is extended to 1.2 m (4 ft).

Photo293 – scale is extended 0.9 m (3 ft).

Photo294 – scale is extended 0.9 m (3 ft).

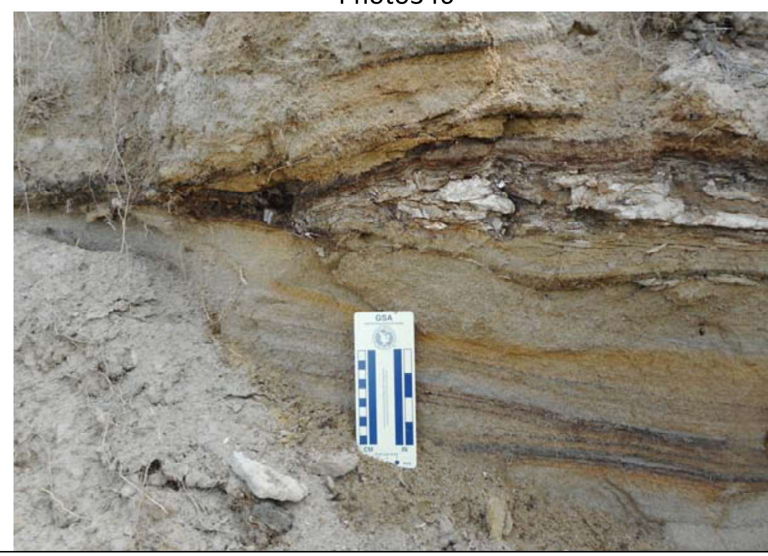
Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo295 – scale is extended to 0.9 m (3 ft).

Photo296

Photo297 – scale is extended to 0.8 m (2.5 ft).

Photo346



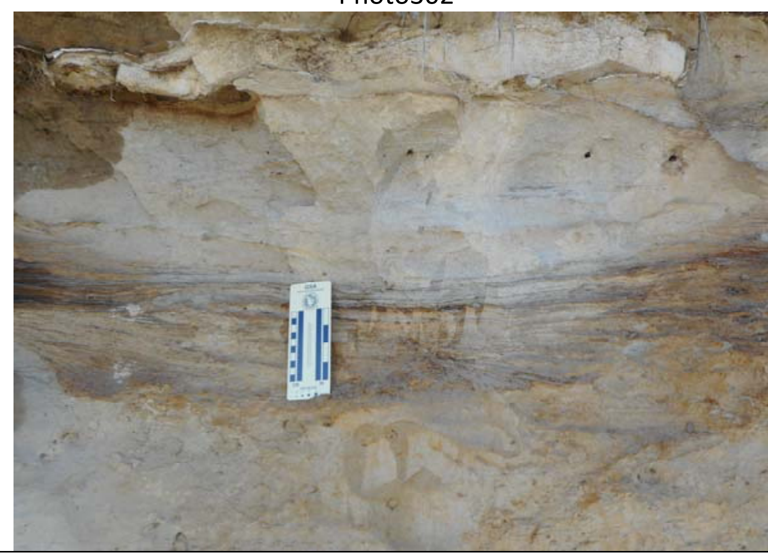
Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo344

Photo345

Photo301 – scale is extended to 1.8 m (6 ft).

Photo302



Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo303

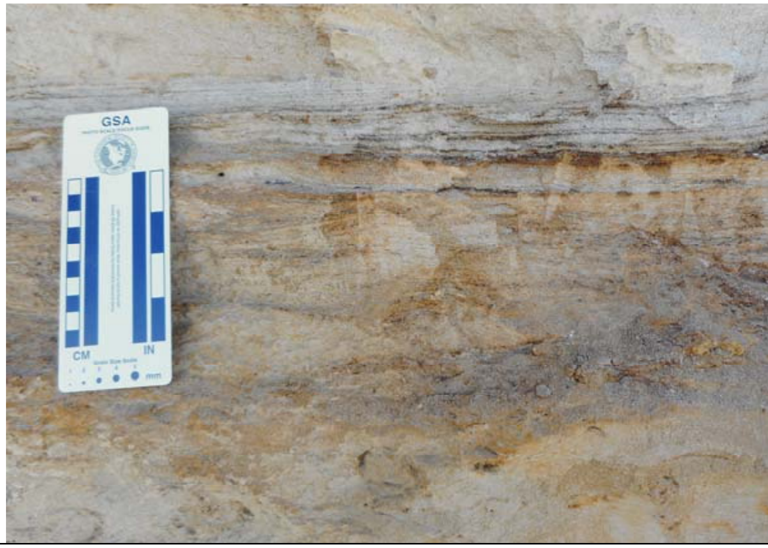


Photo298

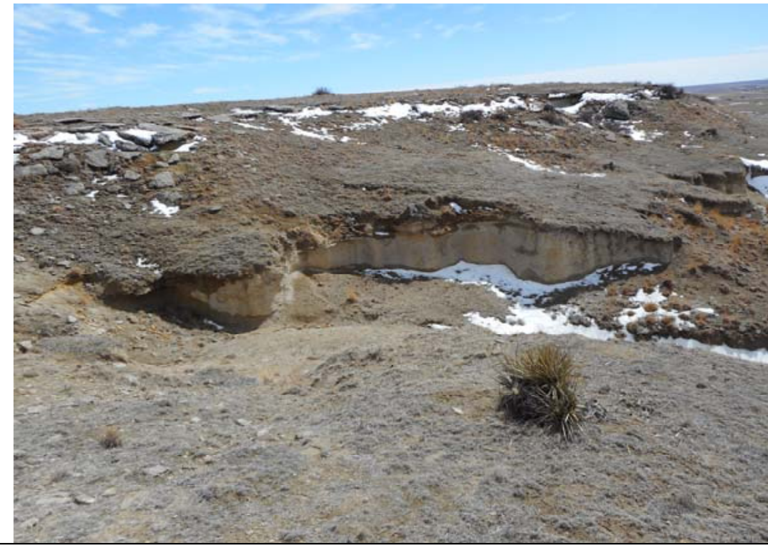


Photo299

Photo305/306 -

Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo307 – visible length of scale is 0.3 m (1 ft). 	Photo304 – scale is 1.8 m (6 ft). 
Photo329 – visible length of scale is 0.7 m (2.4 ft). 	Photo330 – visible length of scale is 0.9 m (3 ft). 

Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo331

Photo326/327

Photo328 – visible length of scale is 1.5 m (5 ft).

Photo325 – visible length of scale is 0.6 m (2 ft).

Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo324 – visible length of scale is 0.4 m (1.2 ft).

Photo338 – scale is 1.2 m (4 ft).

Photo339

Photo341 – scale is 1.2 m (4 ft)

Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo340

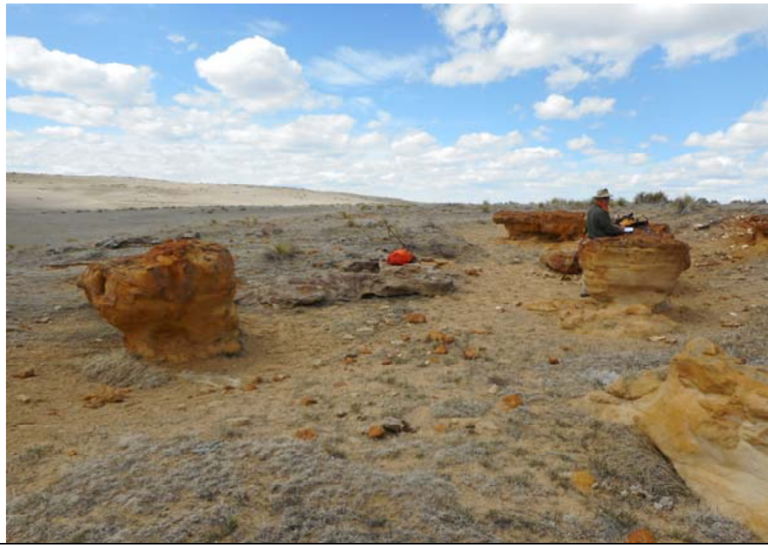


Photo332

Photo333

Photo334

Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

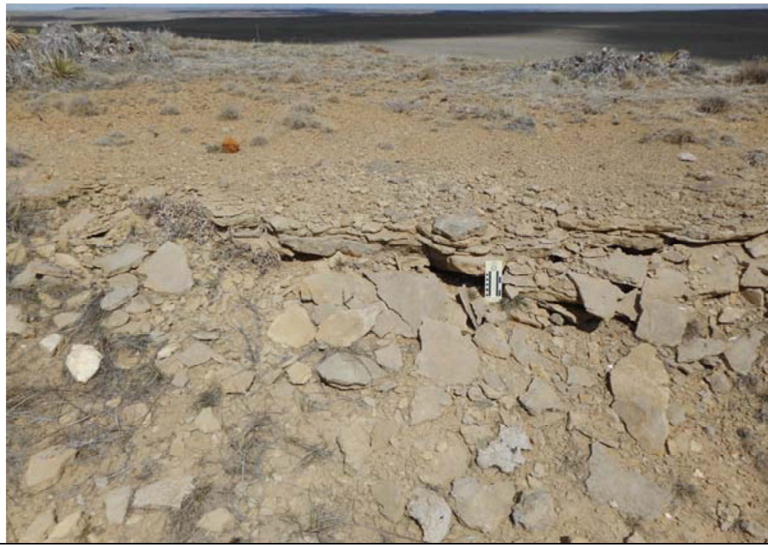
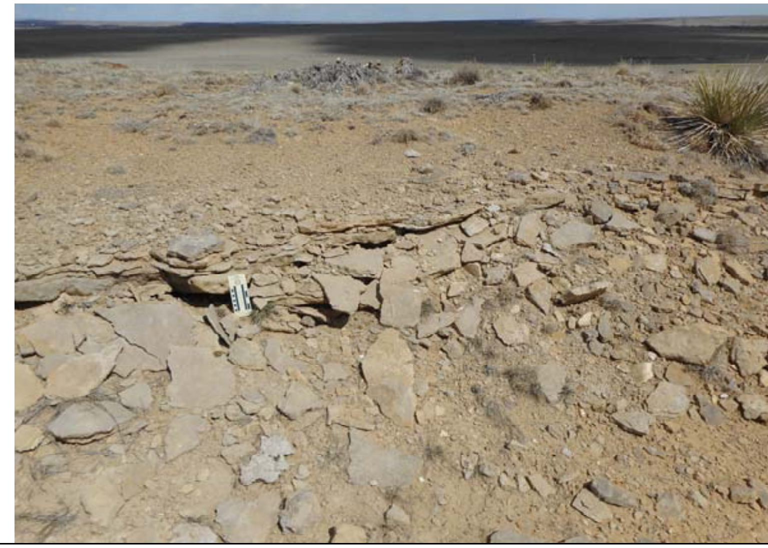
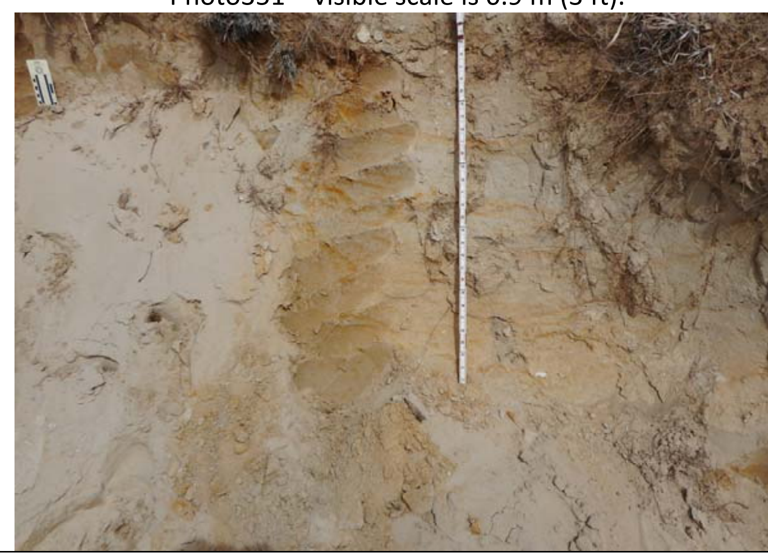
Photo335

Photo336

Photo337

Photo339 – visible length of scale is 0.9 m (3 ft).

Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo342 	Photo343 
Photo350 	Photo351 – visible scale is 0.9 m (3 ft). 

Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo353 – visible scale length is 1.8 m (6 ft).

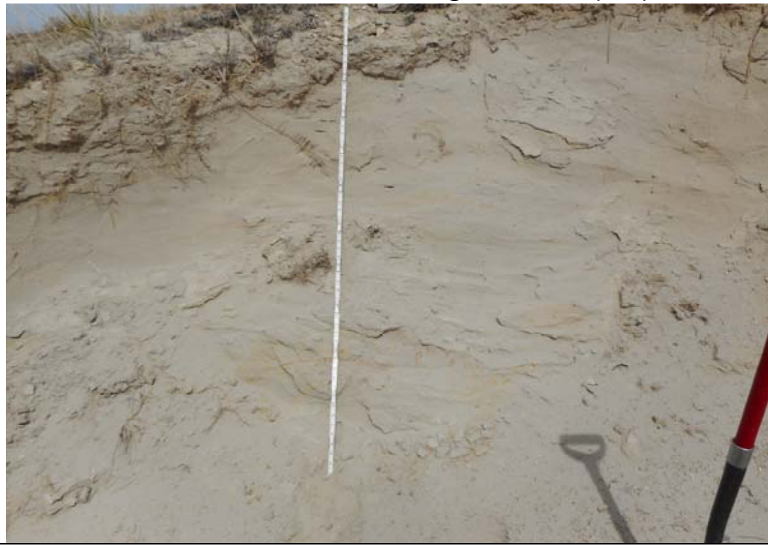


Photo354 – visible scale length is 0.6 m (1.8 ft).

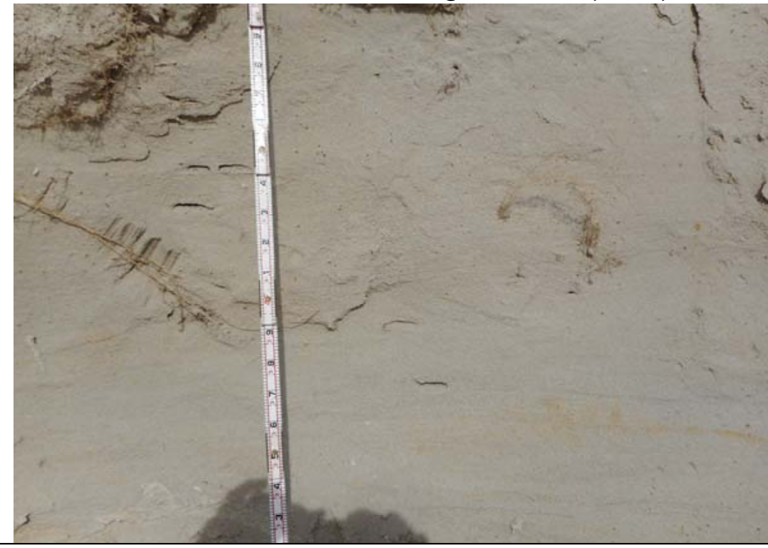


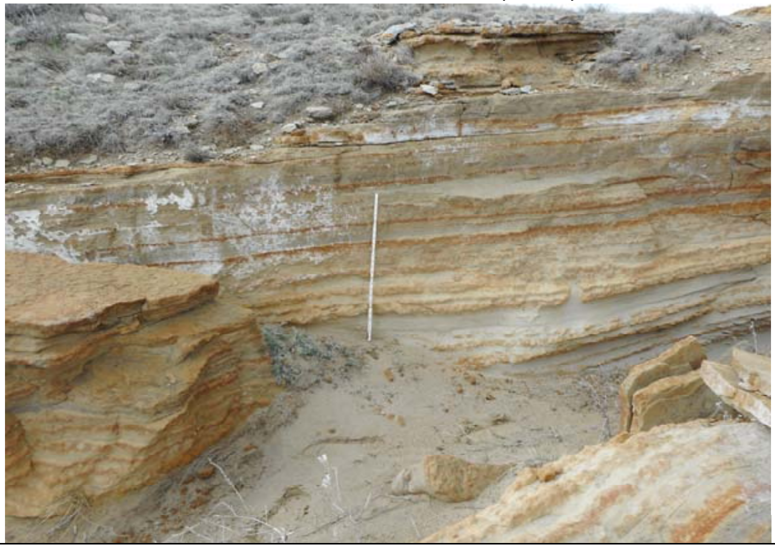
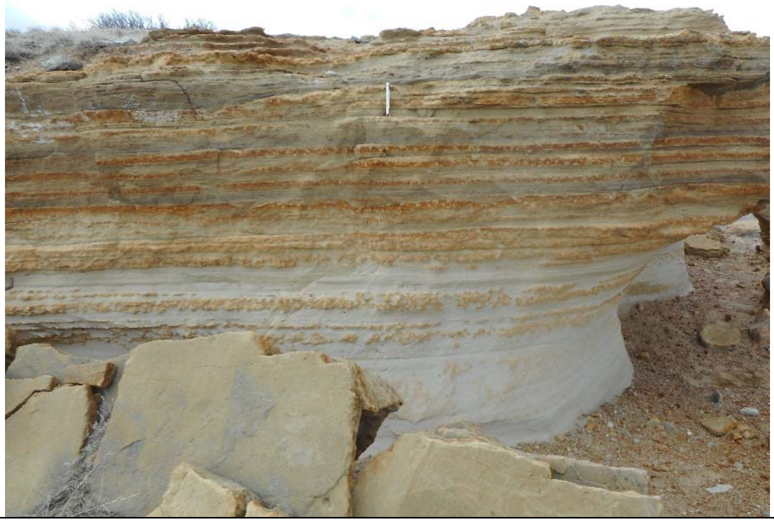
Photo352

Photo356

Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo357 	Photo361 – scale is 1.1 m (3.5 ft). 
Photo372 – rod divisions are 0.1 m (0.3 ft). 	Photo362 – scale is 1.1 m (3.5 ft). 

Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo363 – scale is 0.8 m (2.5 ft). 	Photo364 – scale is 0.2 m (0.6 ft). 
Photo366 – scale is 0.2 m (0.6 ft). 	Photo367 – scale is 0.2 m (0.6 ft). 

Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo368

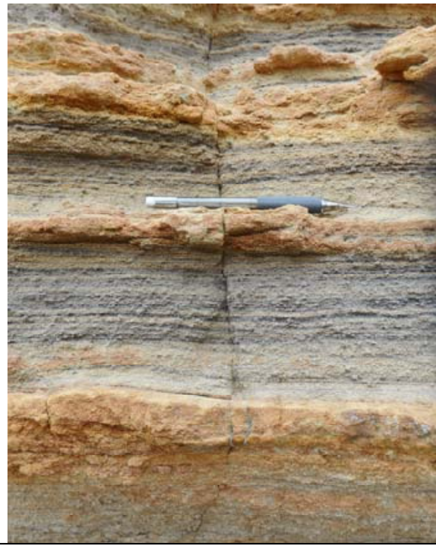


Photo371

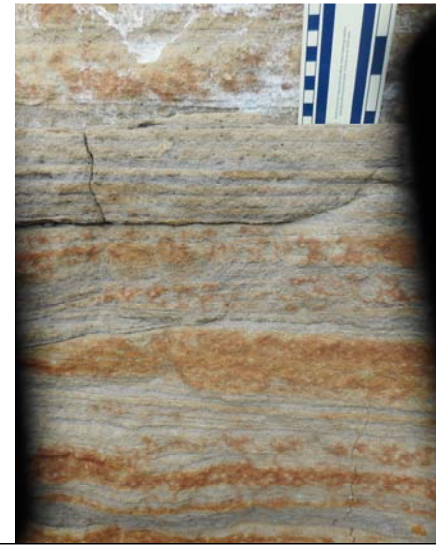


Photo370 – rod divisions are 0.1 m (0.3 ft).

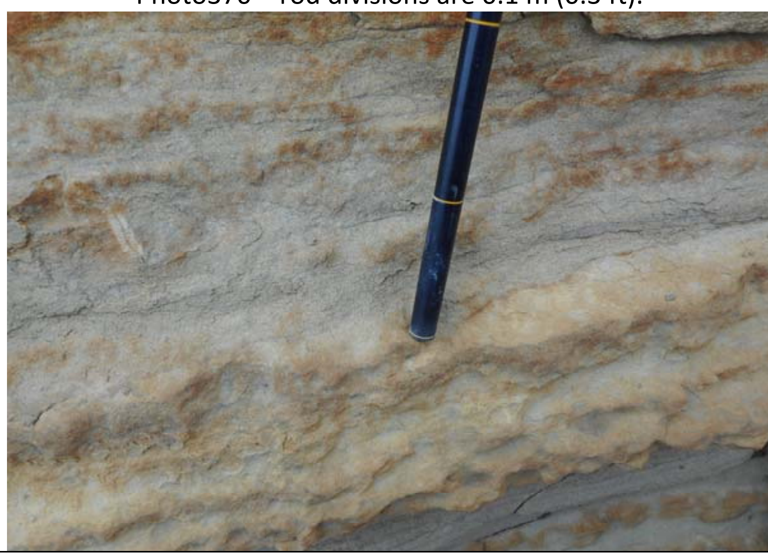
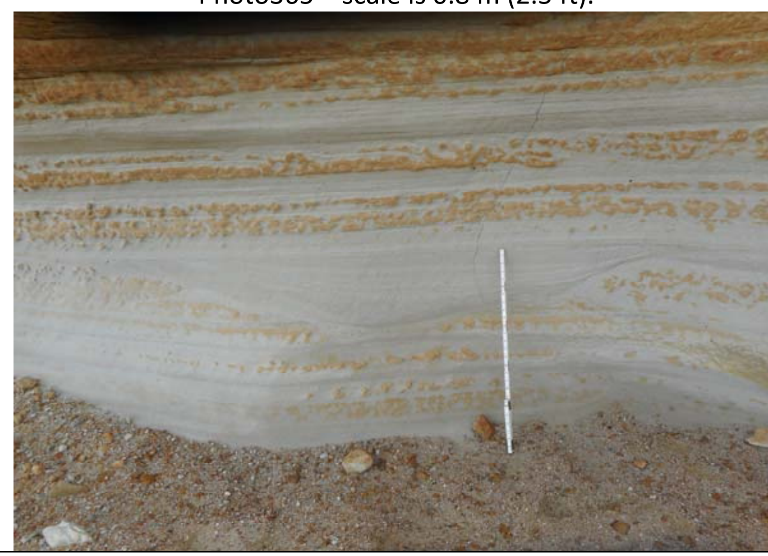


Photo365 – scale is 0.8 m (2.5 ft).



Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo384

Photo385 – rod divisions are 0.1 m (0.3 ft).

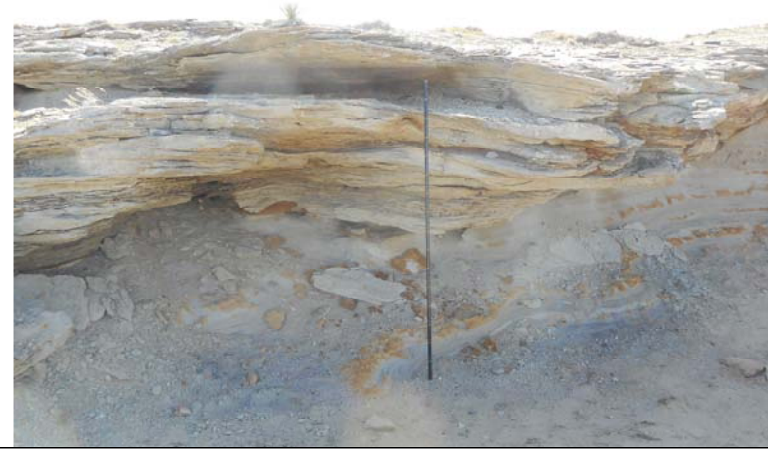
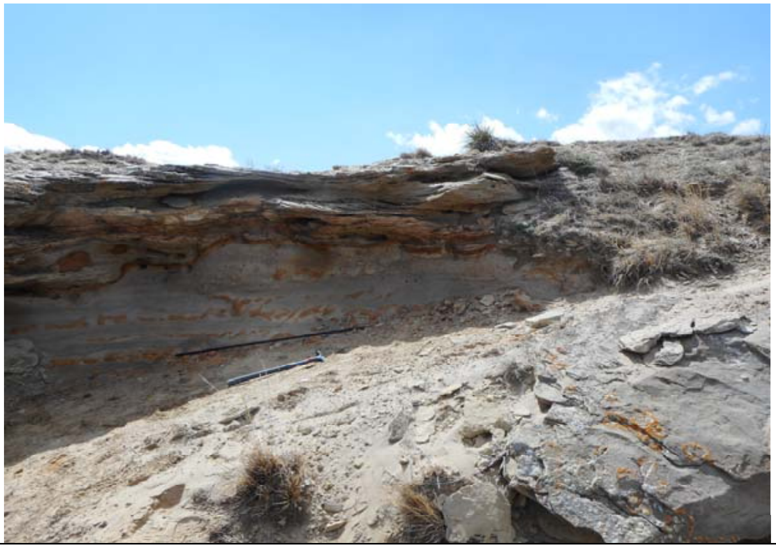


Photo378

Photo380

Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo383	Photo373
	
Photo374	Photo375
	

Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo376

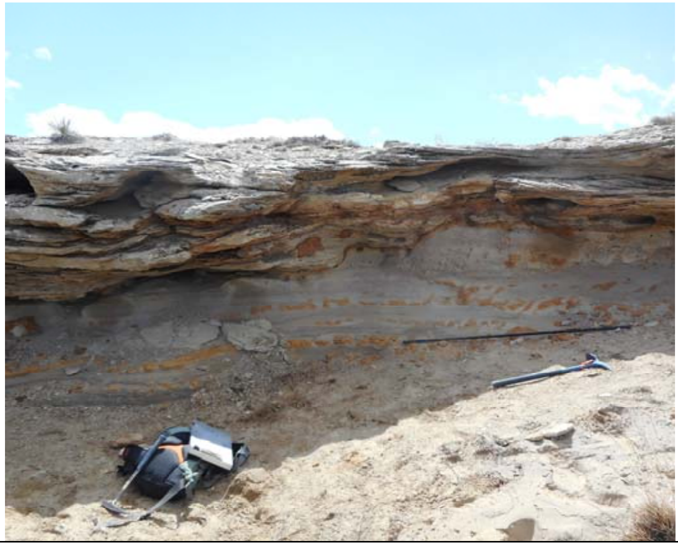


Photo377

Photo379 – rod divisions are 0. 1 m (0.3 ft).

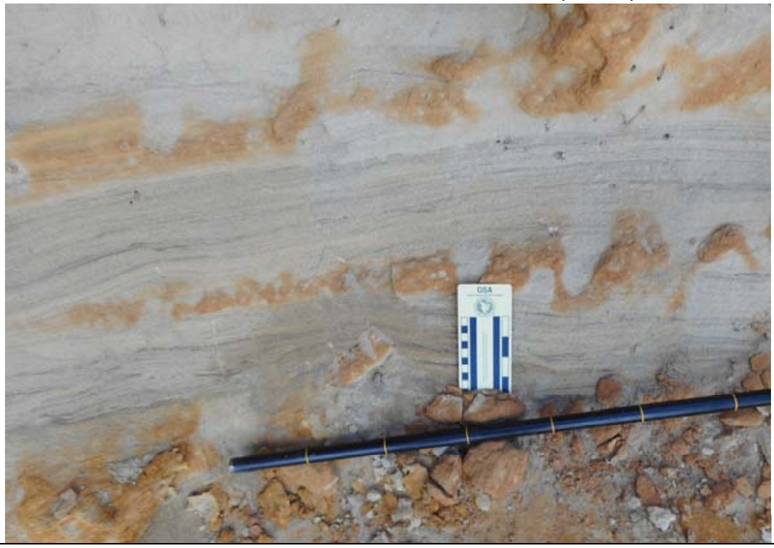


Photo401 – scale is extended to 0.5 m (1.5 ft).

Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo395 – scale is 1.8 m (6 ft).

Photo396

Photo397

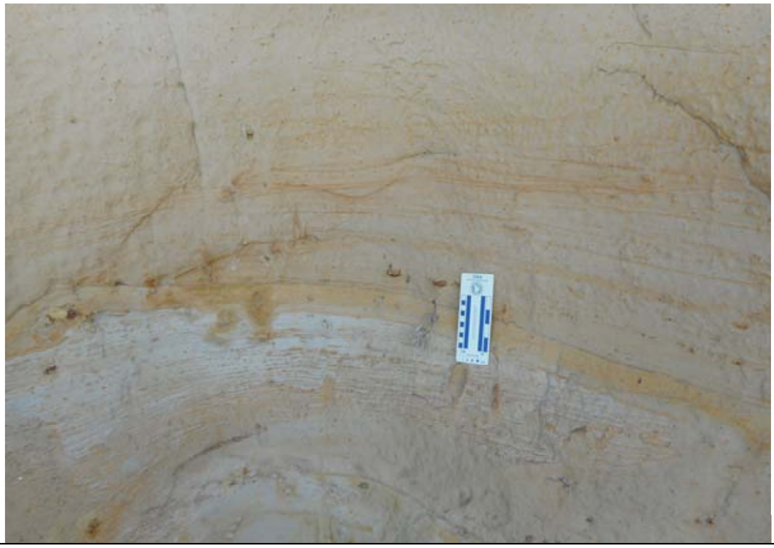


Photo398

Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo399

Photo400 – visible portion of scale is 0.4 m (1.3 ft).

Photo402

Photo403 – scale is 1.5 m (5 ft).

Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo405

Photo404 – scale is 1.2 m (4 ft).

Photo406

Photo408

Photos referenced in the stratigraphic section field notes (in order as referenced) included in this Appendix. Scale card is 16.5 cm (6.5 inches) long, rod divisions are 10 cm (~4 inches). All photos by S. Keller.

Photo407 – visible portion of scale is 1.2 m (4 ft). 	

Appendix D

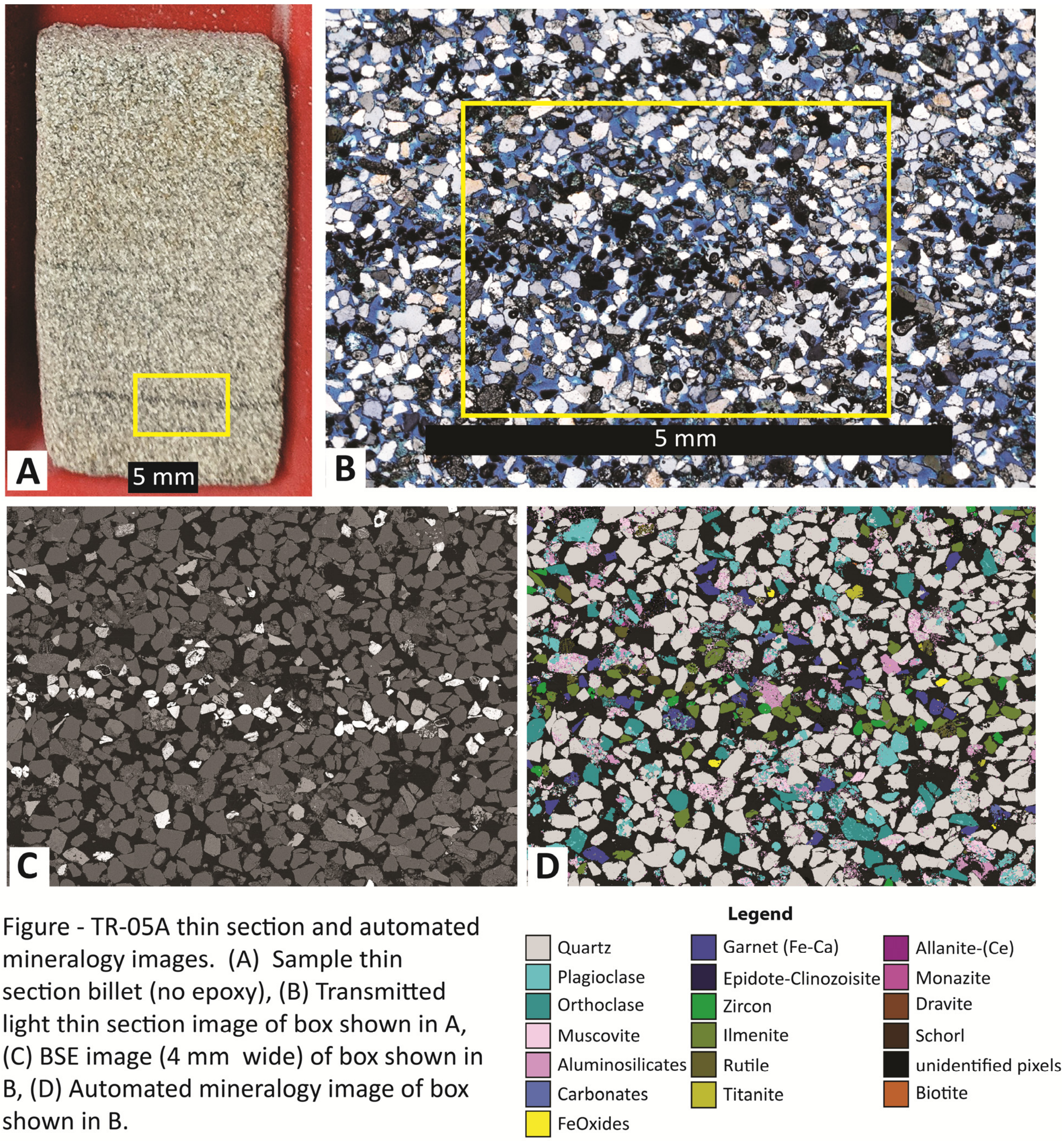


Figure - TR-05A thin section and automated mineralogy images. (A) Sample thin section billet (no epoxy), (B) Transmitted light thin section image of box shown in A, (C) BSE image (4 mm wide) of box shown in B, (D) Automated mineralogy image of box shown in B.

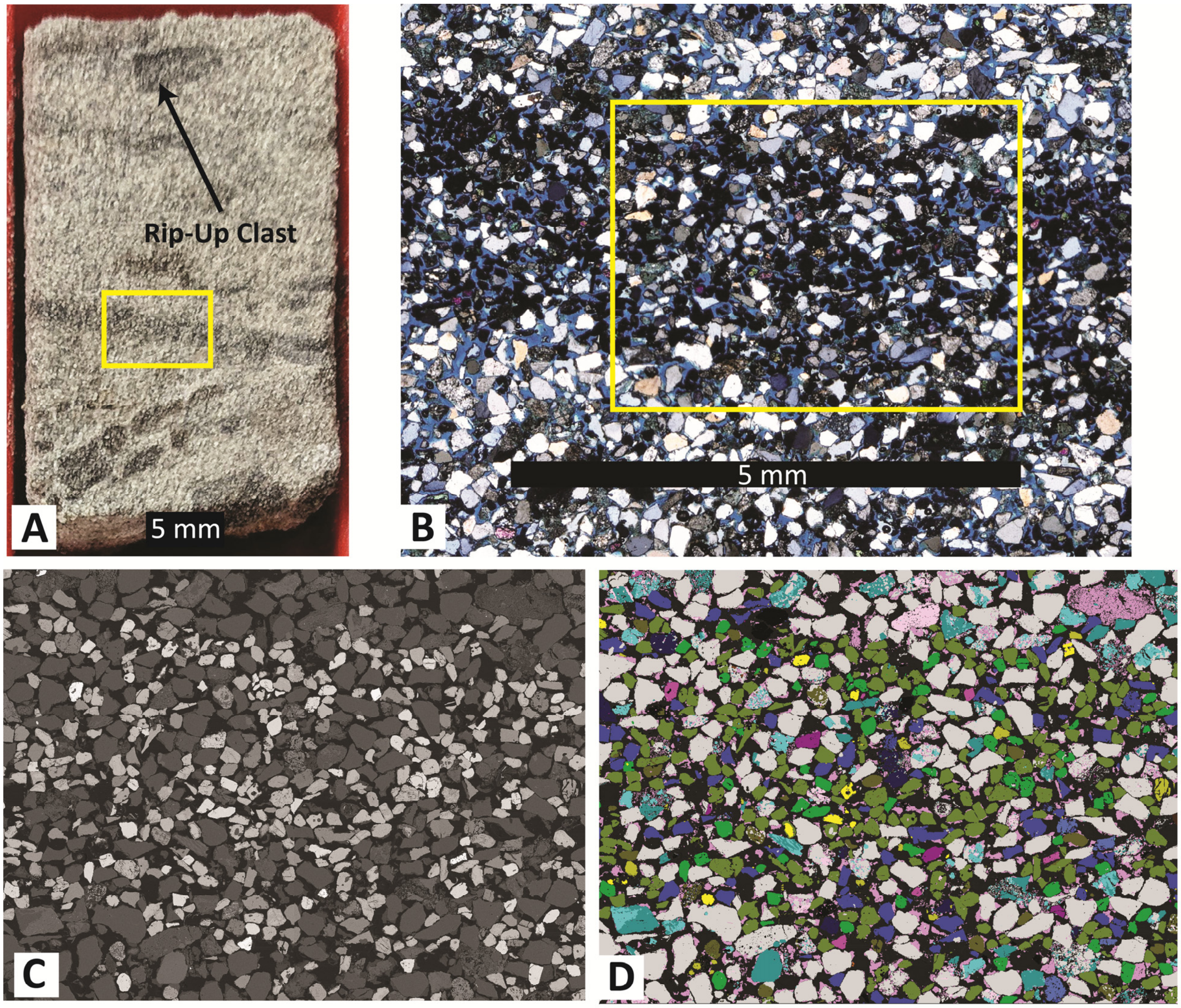


Figure - TR-05C LA#3 thin section and automated mineralogy images. (A) Sample thin section billet (no epoxy), (B) Transmitted light thin section image of box shown in A, (C) BSE image (4 mm wide) of box shown in B, (D) Automated mineralogy image of box shown in B.

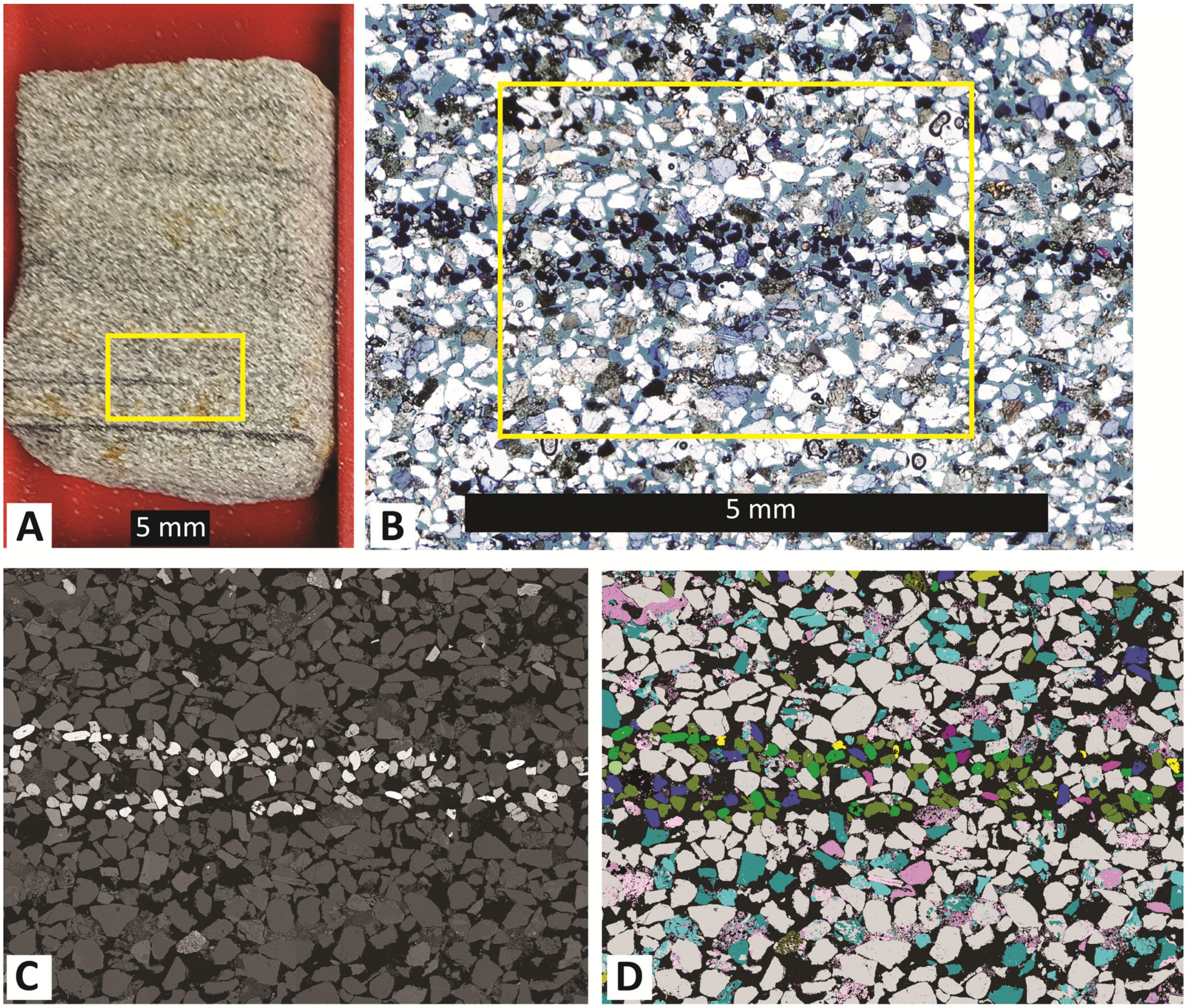


Figure - TR-06A LA2 thin section and automated mineralogy images. (A) Sample thin section billet (no epoxy), (B) Transmitted light thin section image of box shown in A, (C) BSE image (4 mm wide) of box shown in B, (D) Automated mineralogy image of box shown in B.

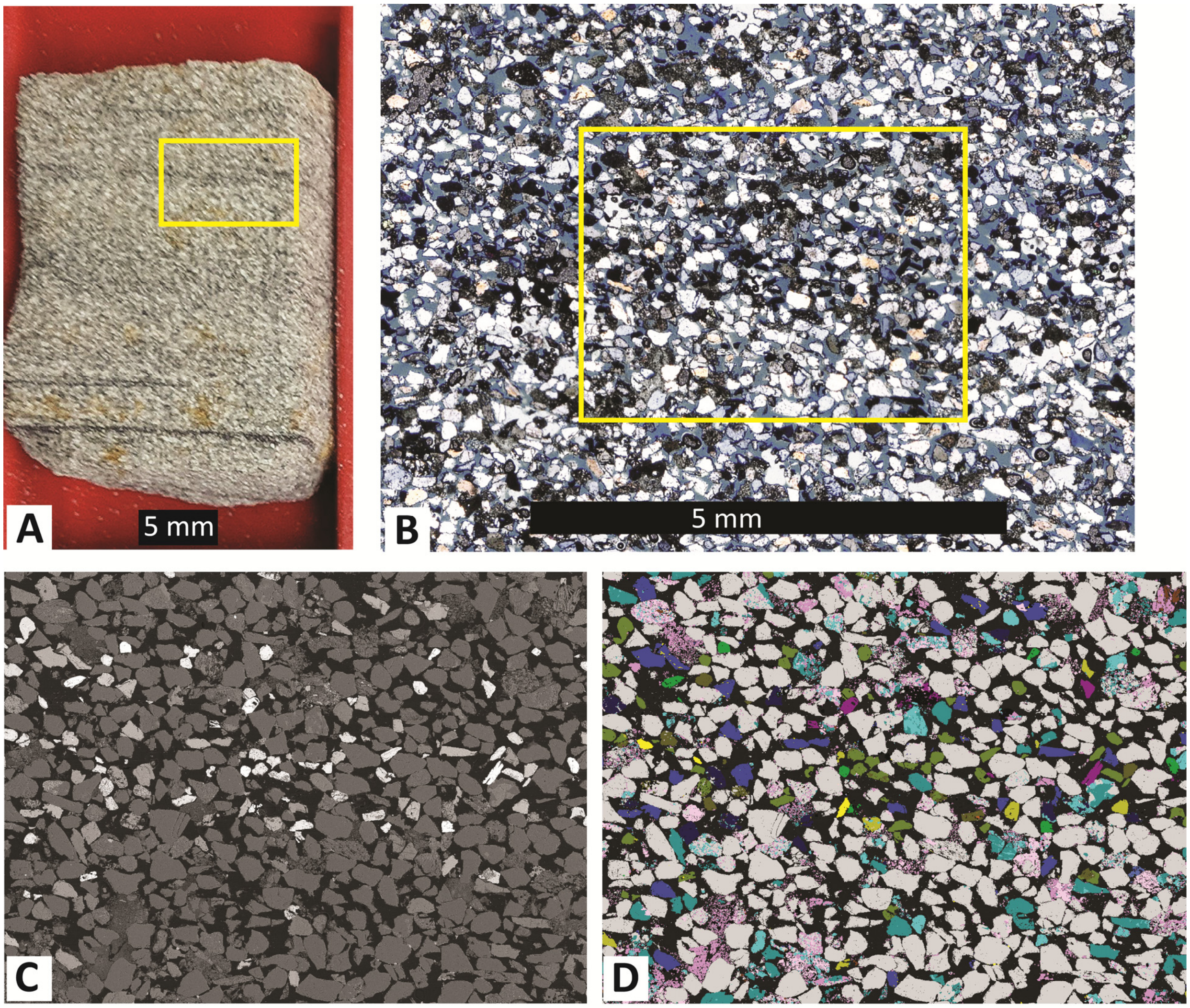


Figure - TR-06A LA3 thin section and automated mineralogy images. (A) Sample thin section billet (no epoxy), (B) Transmitted light thin section image of box shown in A, (C) BSE image (4 mm wide) of box shown in B, (D) Automated mineralogy image of box shown in B.

Legend

- Quartz
- Plagioclase
- Orthoclase
- Muscovite
- Aluminosilicates
- Carbonates
- Garnet (Fe-Ca)
- Epidote-Clinozoisite
- Zircon
- Ilmenite
- Rutile
- FeOxides
- Allanite-(Ce)
- Dravite
- Schorl
- unidentified pixels
- Biotite
- Titanite