Interpreting the past, providing for the future

Critical-Mineral-Bearing Paleoplacers in the Basal Cambrian Flathead Sandstone and Other Radioactive Conglomerates, Wyoming: Geochemistry and Mineralogy

Derek T. Lichtner, Jon M. Krupnick, Christopher J. Doorn, and Patricia M. Webber

Open File Report 2023-2
December 2023

Wyoming State Geological Survey

Erin A. Campbell, Director and State Geologist

Critical-Mineral-Bearing Paleoplacers in the Basal Cambrian Flathead Sandstone and Other Radioactive Conglomerates, Wyoming: Geochemistry and Mineralogy

Derek T. Lichtner, Jon M. Krupnick, Christopher J. Doorn, and Patricia M. Webber

Layout by James R. Rodgers

Open File Report 2023-2
Wyoming State Geological Survey
Laramie, Wyoming: 2023

Open File Reports are preliminary and usually require additional fieldwork and/or compilation and analysis; they are meant to be a first release of information for public comment and review. The Wyoming State Geological Survey welcomes any comments, suggestions, and contributions from users of the information.

Citation: Lichtner, D.T., Krupnick, J.M., Doorn, C.J., and Webber, P.M., 2023, Critical-mineral-bearing paleoplacers in the basal Cambrian Flathead Sandstone and other radioactive conglomerates, Wyoming—Geochemistry and mineralogy: Wyoming State Geological Survey Open File Report 2023-2, 58 p., https://doi.org/10.15786/24279697.

Table of Contents

List of Figures

List of Tables

ABSTRACT

Fluvial placers are potential sources of critical and economic minerals. In Wyoming, historical data suggest paleoplacers in the Middle Cambrian Flathead Sandstone, Paleoproterozoic Jack Creek Quartzite, Paleoproterozoic Magnolia Formation, and Eocene Wind River Formation are enriched in rare earth and other elements. With the goal of acquiring analyses of these typically radioactive conglomerates using modern geochemical and mineralogical methods, 66 samples were collected and analyzed from known or potential occurrences throughout Wyoming.

Forty-three samples from the basal conglomerate of the Flathead Sandstone were collected and analyzed. Geochemical measurements averaged 898 parts per million (ppm) total rare earth elements (REEs), with a range of 54.9–9,960 ppm (average total rare earth oxides [REOs] of 1,050 ppm, with a range of 64.8–11,700 ppm). REEs in the Flathead consist predominantly of light REEs (LREEs). Optical petrography and scanning electron microscopy (SEM) imaging of select samples indicated that the LREE are hosted by fine-grained detrital monazite. Although the Bald Mountain deposit in the northern Bighorn Mountains is the most studied deposit of this type in Wyoming, minor REE enrichment was also confirmed in the southern Bighorn Mountains, Wind River Basin, and Rattlesnake Hills. At most locations, the radioactive conglomerates of the Flathead Sandstone are very poorly exposed, and their dimensions are unknown.

Radioactive conglomerates have also been reported in the Precambrian metasedimentary rocks of the Sierra Madre and Medicine Bow Mountains. Like in the Flathead Sandstone, these mineralized conglomerates overlie major unconformities. In the Sierra Madre, the most highly enriched intervals are in the Deep Gulch Conglomerate member of the Jack Creek Quartzite of the Paleoproterozoic Phantom Lake Suite. Six samples collected from the Phantom Lake Suite averaged 245 ppm total REEs, with a range of 55.8–507 ppm (average total REO of 294 ppm, with a range of 66.4–605 ppm). Unlike the other radioactive conglomerates investigated for this study, elevated REE content in the Deep Gulch Conglomerate of the Phantom Lake Suite consisted mostly of heavy REEs (HREEs), with an HREE fraction (total HREEs divided by total REEs) of 0.42. The primary host mineral of the HREEs is uncertain. Xenotime was observed, as well as abundant and possibly HREE-enriched zircon associated with muscovite. The radioactivity of the conglomerates may be due in large part to thorium-bearing minerals other than monazite. SEM imaging revealed an unidentified thorium-iron-oxide phase as well as micron-scale thorium minerals, possibly coffinite. Seven samples from the Paleoproterozoic Deep Lake Group in the Medicine Bow Mountains exhibited elevated LREE concentrations, with total REE concentrations averaging 200 ppm, with a range of 20.3–493 ppm (average total REO of 236 ppm, with a range of 24.3–579 ppm). Mineralogical analysis of a sample from the Magnolia Formation near Onemile Creek revealed very fine monazite as well as fine-grained thorium-iron-oxide phases similar to those observed in the Phantom Lake Suite.

Although radioactivity in the Eocene Wind River Formation is often associated with uranium roll-front deposits, it also occurs due to the presence of thorium-bearing monazite paleoplacers. Most of these occurrences are in the Shirley Rim-Bates Hole area in central Wyoming, although a small number are reported elsewhere. For this study, 10 samples were collected from conglomerates or gravel residuum near the top of the Wind River Formation. Geochemical analysis of these samples averaged 954 ppm total REEs, with a range of 164–2,190 ppm. Elevated REEs in the Eocene monazite placers were primarily LREEs.

INTRODUCTION

The U.S. Geological Survey (USGS) categorizes critical minerals as those that are vital for the economic and national security of the United States (fig. 1). These minerals are not only crucial in the production of essential goods, but they also have supply chains that are susceptible to disruption. In response to Executive Order 13817, the USGS identified 33 individual minerals and two mineral groups as critical minerals in 2018 (U.S. Department of the Interior, 2018). This list was revised in 2022 and expanded to 50 specific mineral commodities (U.S. Geological Survey, 2022).

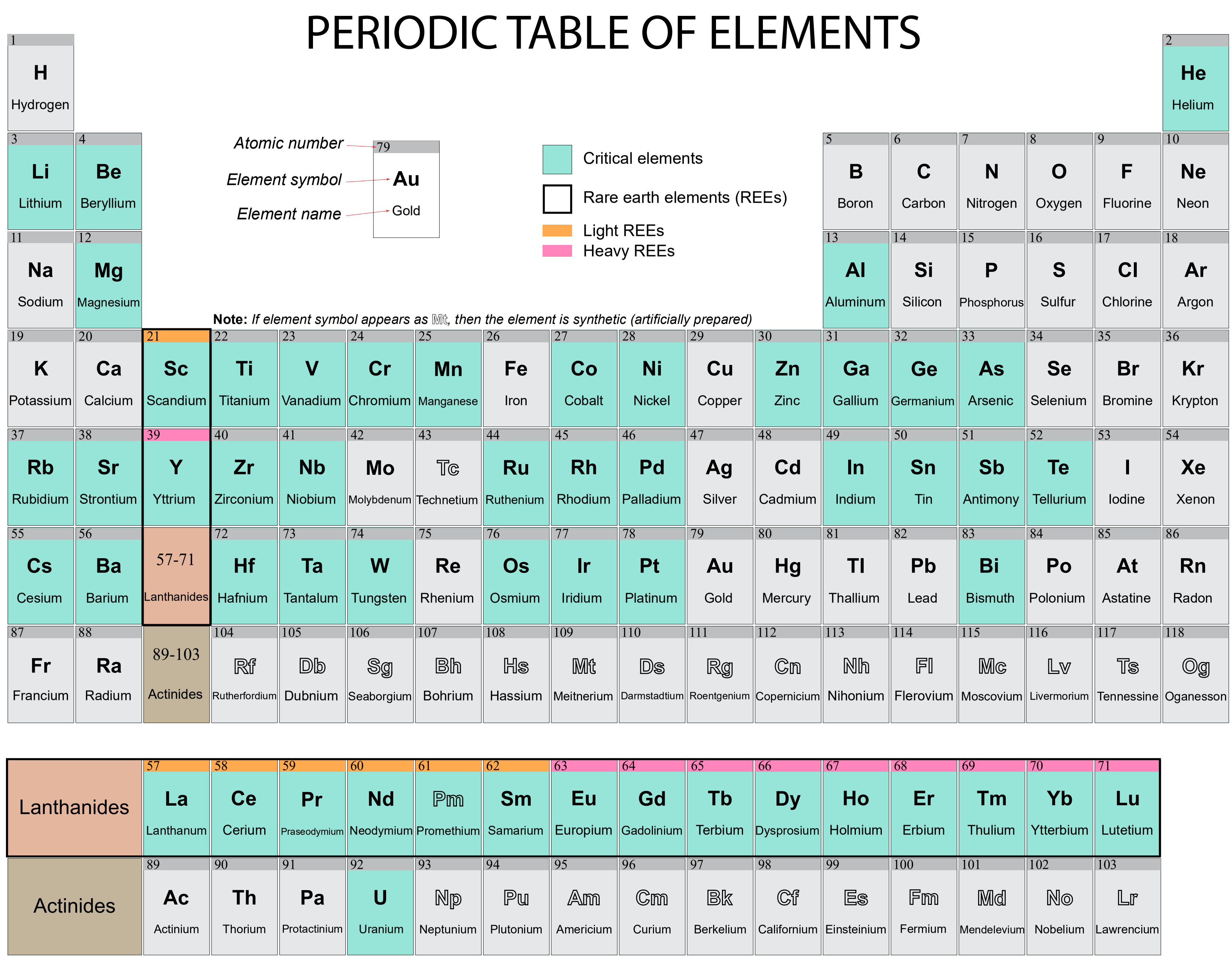

Figure 1. Periodic table highlighting elements deemed critical in 2018 and 2022 (U.S. Department of the Interior, 2018, 2022). In 2022, uranium, helium, strontium, rhenium, and potash were removed, while nickel and zinc were added to the list of critical elements.

The critical minerals most relevant to this study are the rare earth elements (REE). REEs consist of 15 lanthanide metals, from lanthanum to lutetium, excluding promethium, which does not naturally occur. Often, scandium and yttrium are considered REEs because of their chemical resemblance to lanthanides. Yttrium is also frequently found in the same deposits. For the purpose of this report, the term "REE" represents all 17 of these elements. REEs are also typically divided into "light" REEs (LREEs) and "heavy" REEs (HREEs) based on their atomic numbers. The dividing line varies among studies. In this report, following a classification scheme modified from Henderson (1984), we consider LREEs to range from lanthanum to samarium, and HREEs to span europium to lutetium, including yttrium. Even though yttrium has a smaller atomic number, it is often classified as a HREE due to its geochemical characteristics. Scandium, although it is often considered a REE, usually is not grouped with either LREEs or HREEs.

REEs find applications in numerous areas, such as specialty glass products, permanent magnets, steel manufacturing, batteries, and various electronic components (Van Gosen and others, 2017). In recent years, the demand for praseodymium, neodymium, terbium, and dysprosium has been on the rise owing to their use in emerging green technologies (Liu and others, 2023).

There are 245 recognized species of REE-bearing minerals that belong to different groups, such as fluorocarbonates, phosphates, silicates, and others. The production of REEs typically involves only a handful of these minerals, including bastnasite, monazite, xenotime, rhabdophane, allanite, loparite, and fluorapatite (Van Gosen and others, 2017). Monazite, a thorium- and REE-bearing phosphate mineral, is sometimes concentrated in placer deposits (Van Gosen and others, 2017).

Placer deposits are concentrations of heavy minerals that form in stream beds, on beaches, or in other depositional environments. The formation of fluvial and erosional placer deposits, like those described in this report, involves several steps. The process begins with the weathering and erosion of a source rock that contains valuable and "heavy," or dense, minerals. The source rock is broken down into smaller fragments or soil by natural forces such as wind, rain, and temperature change, thereby liberating the heavy minerals. Mineral grains are then transported by water or wind. In the case of fluvial placers, the lighter, less dense materials are carried further downstream, while the heavier, more dense minerals—such as gold, monazite, and others—are left behind. Over time, the combined processes of weathering, transportation, and deposition can lead to the local accumulation of heavy minerals.

METHODS

The primary goal of this study was to enhance understanding of the geochemical makeup of REE-bearing fluvial placers in Wyoming. For this research, we collected samples from several stratigraphic intervals throughout the state: the Jack Creek Quartzite of the Paleoproterozoic Phantom Lake Suite, the Paleoproterozoic Magnolia Formation of the Deep Lake Group, the Middle Cambrian Flathead Sandstone, and the Eocene Wind River Formation. Although these strata each have very different geologic histories, they all contain, or potentially contain, placer deposits in radioactive conglomerates, with a majority of occurrences positioned above major unconformities.

At each deposit location, we took multiple samples, typically composites from the entire thickness at the site. We used a scintillation meter to measure the level of radioactivity at each location, which also helped us decide where to collect samples. Although we tried to take samples that represented each deposit as a whole, it is important to note that all samples were collected from surface outcrops. In addition, sampling density was limited due to the statewide scope of this project. As a result, the datasets we present here do not provide a full assessment of the quality of the ore.

We chose the samples for geochemical analysis based on initial semi-quantitative data we obtained with a portable X-ray Fluorescence (pXRF) device. A total of 66 samples were geochemically analyzed. Thirteen of these were from the metasedimentary Precambrian units, 43 were from the Flathead Sandstone, and the remaining 10 were from the Wind River Formation. Major element oxides were measured by inductively coupled plasma atomic emission spectroscopy (ICP-AES) after preparing the samples with lithium borate fusion. For trace element analyses, the samples were prepared by lithium borate fusion or, for trace metals, with four-acid digestion, and measured with ICP-AES. Total carbon and sulfur were measured using infrared (IR) spectroscopy. The geochemical analyses were performed by ALS Global Ltd.

We also conducted mineralogical analysis on selected samples. Wagner Petrographic, Inc. prepared a number of thin sections for this purpose. Examination of samples in thin section was crucial for identifying unknown mineral phases and inspecting cementation and possible alteration. We examined samples in both plane- and cross-polarized light, and also acquired backscattered electron (BSE) images of select polished thin sections using a scanning electron microscope (SEM) at the Department of Geology and Geophysics at the University of Wyoming. To help identify minerals, we also collected semi-quantitative SEM energy dispersive spectroscopy (SEM-EDS) measurements. To better understand the mineral composition and the distribution of elements, certain samples were subjected to bulk-mineral analysis with QEMSCAN by ALS metallurgy. The chemical compositions of minerals mentioned in this report are provided in table 1.

Table 1. Chemical compositions of minerals mentioned in this report.

Mineral name	Generalized chemical formula
Allanite (epidote)	$(Ce,Ca,Y,La)_2(Al,Fe^{+3})_3(SiO_4)_3(OH)$
Apatite	$Ca_5(PO_4)_3(F,Cl,OH)$
Bastnaesite(?)	$(La,Ce,Y)CO_3F$
Biotite	$K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$
Chlorite	$(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2\cdot(Mg,Fe)_3(OH)_6$
Coffinite	$U(SiO_4) \cdot nH_2O$
Columbite	$Fe^{2+}Nb_2O_6$
Fluoroapatite	$Ca_5(PO_4)_3F$
Hematite	Fe_2O_3
Huttonite	$ThSiO_4$
Ilmenite	$FeTiO_3$
Loparite	$(Na,REE)_2Ti_2O_6$
Monazite	$(LREE,Th)PO_4$
Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$
Potassium feldspar	$K(AlSi_3O_8)$
Quartz	SiO_2
Rhabdophane	$Ca(REE)(CO_3)_2F$
Rutile	TiO_2
Thorite	$ThSiO_4$
Tourmaline	$(Na,Ca)(Li,Mg,Al)(Al,Fe,Mn)_6(BO_3)_3(Si_6O_{18})(OH)_4$
Uraninite	UO_2
Xenotime	$(Y,HREE)PO_4$
Zircon	$ZrSiO_4$

Instead of the standard practice of comparing elemental concentrations, particularly REEs, to chondrite compositions, we compared the relative abundances of different elements against the average composition of the upper continental crust (UCC; table 2; Rudnick and Gao, 2014). For this dataset, normalization in this manner better emphasizes the differences between samples rich in trace elements and those without significant concentrations. Because the data often do not follow a normal distribution, the median and the first and third quartiles—instead of the mean and standard deviation—are displayed on plots that show data for more than eight samples. To enable comparison between major elements and trace elements, all tables and plots report elemental, not oxide, concentrations. Conversion factors for oxides associated with critical or economically significant minerals in these deposits are provided in table 3. Previous reports sometimes presented thorium and uranium concentrations as "equivalent," indicating that these were estimates based on spectroscopic data. In this report, we precede such measurements with the term "equivalent" (as in "equivalent thorium") to distinguish them from more accurate chemical methods.

Table 2. Average concentration in upper continental crust of elements detected in this study related to critical or economic minerals, modified from Rudnick and Gao (2014). In ascending order of atomic number. *Converted from major element oxide concentrations, in percent, of MgO=2.48, Al_2O_3=15.4, TiO_2=0.64, MnO=0.1, and FeO=5.04.

Element	Concentration in upper continental crust (X_{UCC}; ppm)	Element	Concentration in upper continental crust (X_{UCC}; ppm)
Li	24	Cs	4.9
Be	2.1	Ba	628
Mg*	15,000	La	31
Al*	82,500	Ce	63
Sc	14	Pr	7.1
Ti*	3,800	Nd	27
V	97	Sm	4.7
Cr	92	Eu	1.0
Mn*	770	Gd	4.0
Fe*	39,200	Tb	0.7
Co	17.3	Dy	3.9
Ni	47	Ho	0.83
Zn	67	Er	2.3
Ga	17.5	Tm	0.3
Ge	1.4	Yb	1.96
As	4.8	Lu	0.31
Rb	84	Hf	5.3
Y	21	Ta	0.9
Zr	193	W	1.9
Nb	12	Pt	0.001
Pd	0.001	Au	0.002
Ag	0.053	Bi	0.16
In	0.056	Th	10.5
Sn	2.1	U	2.7
Sb	0.40		

Table 3. Element-to-oxide stoichiometric conversion factors for some major elements and ore elements relevant to this study.

Element	Oxide	Factor
Be	BeO	2.776
Mg	MgO	1.658
Al	Al_2O_3	1.890
Sc	Sc_2O_3	1.534
Ti	TiO	1.668
V	V	1.785
Mn	MnO	1.291
Fe	FeO	1.287
Fe	Fe_2O_3	1.430
Y	Y	1.270
Zr	ZrO	1.351
Sn	SnO	1.270
Nb	Nb	1.431
La	La_2O_3	1.173
Ce	Ce_2O_3	1.171
Pr	Pr_2O_3	1.170
Nd	Nd	1.166
Sm	Sm_2O_3	1.160
Eu	Eu_2O_3	1.158
Gd	Gd_2O_3	1.153
Tb	Tb_2O_3	1.151
Dy	Dy_2O_3	1.148
Ho	Ho_2O_3	1.146
Er	Er_2O_3	1.144
Tm	Tm_2O_3	1.142
Yb	Yb_2O_3	1.139
Lu	Lu_2O_3	1.137
Hf	HfO_2	1.179
Th	ThO_2	1.138
U	U_3O_8	1.179

PLACERS IN THE BASAL CONGLOMERATE OF THE FLATHEAD SANDSTONE

Geologic Background

The Flathead Sandstone is the lowermost Phanerozoic formation in most of Wyoming. It was deposited during the Middle Cambrian, approximately 520 million years ago. Throughout the region, the Flathead nonconformably overlies Precambrian crystalline and metasedimentary rocks. This unconformity represents roughly 2 billion years of missing time. Relief of the erosional surface is in some places as great as 120 m (Bell, 1970), although it is usually less. Highly weathered paleoregoliths of crystalline rock are preserved at the contact in some places. The basement rock on which the Flathead Sandstone rests varies (Sims and others, 2001). In some areas the Flathead was deposited on gneiss and migmatite (for example, at Prospect Creek in the southern Bighorn Mountains), in other places on metasedimentary and metavolcanic rocks (for example, Meadow Gulch in the southern Wind River Range), and most often atop intrusive igneous rocks, mostly granite (such as at Bald Mountain in the northern Bighorn Mountains or in the western the Rattlesnake Hills). Where radioactive conglomerates have been reported in the Flathead Sandstone, these different basement compositions are all Neoarchean in age and considered part of the Wyoming Craton.

Much of the Flathead Sandstone was deposited during overall transgression of a seaway from west to east across the region over the course of about 50 million years. Although some shorter-period sea-level fluctuations have been identified within the formation (Middleton, 1980; Middleton and others, 1980), the Flathead overall fines and deepens upward. Much of the formation is composed of coastal and near-shore deposits, but the base of the formation consists of clast- and matrix-supported conglomerates and coarse-grained sandstones that have been interpreted as having been deposited in west-flowing braided-stream systems (Middleton, 1980; Middleton and others, 1980). This basal conglomerate is poorly to moderately sorted and contains angular to subangular clasts of granitic and gneissic basement rock, typically less than 4 cm in diameter.

Additional information on the geologic history and stratigraphy of the Flathead Sandstone can be found in Blackwelder (1918), Miller (1936), Stipp (1947), Thomas (1948, 1949, 1950, 1951), Cygan and Koucky (1963), Bell (1970), Bell and Middleton (1978), Degenstein (1978), Middleton (1980), Middleton and others (1980), Sando and Sandberg (1987), Boyd (1993), Beebee and Cox (1998), and Malone and others (2017).

Previous Exploration

Paleoplacers at the base of the Flathead Sandstone were first explored as a source of gold (Darton, 1906; Darton and Salisbury, 1906), although mining efforts were not sustainable. Half a century later, monazite placers in the same stratigraphic interval were investigated as a potential source of thorium (Wilson, 1951; Kline and Winkel, 1952; McKinney and Horst, 1953; Borrowman and Rosenbaum, 1962). Although much of this work revolved around the Bald Mountain occurrence in the northern Bighorn Mountains, later reports for the National Uranium Resource Evaluation (NURE) program indicated that thorium enrichment is present in the basal Flathead Sandstone elsewhere in Wyoming (fig. 2; Damp and Brown, 1982; Damp and others, 1982; Garrand and others, 1982; Gebhardt and others, 1982; Griffin and others, 1982). Because uranium, not thorium, was the target of these efforts, these radioactive conglomerates were given only a cursory treatment, with limited reported data and brief or nonexistent descriptions. King (1991) and Hausel and Graves (1996) later provided some commentary on these earlier datasets, suggesting that some of the radioactive conglomerates may be paleoplacers. Most of these potential deposits are probably small, and all of them are very poorly exposed, so little is known about their dimensions.

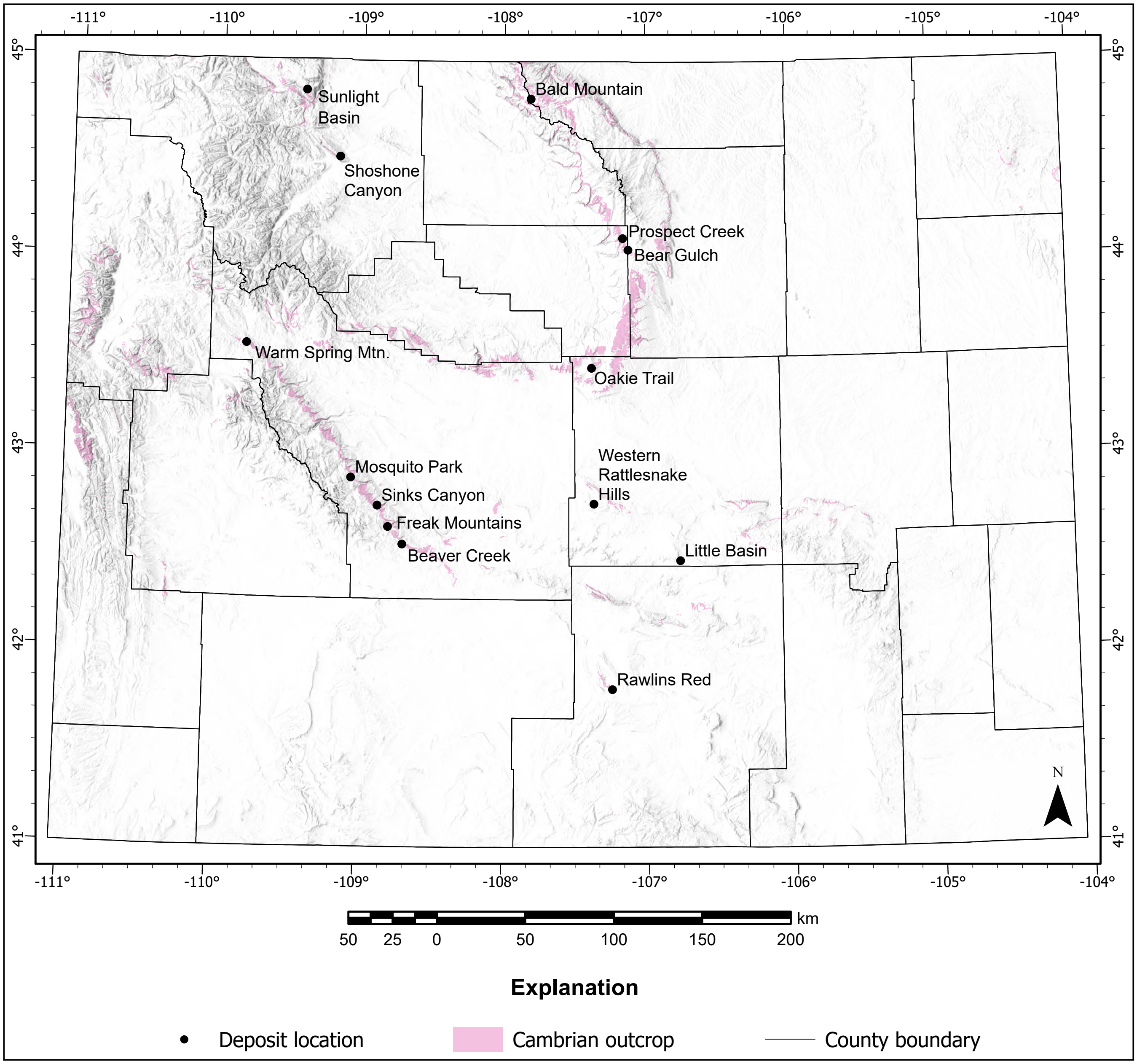

Figure 2. Reported locations of paleoplacer deposits or anomalous thorium concentrations in the basal conglomerate of the Cambrian Flathead Sandstone.

In the 2010s, the Flathead Sandstone was given renewed consideration by the Wyoming State Geological Survey (WSGS) as a potential source of REEs. Sutherland and others (2013) and Sutherland and Cola (2015, 2016) collected and analyzed a small number of grab samples, mostly from Bald Mountain in the northern Bighorn Mountains but also from locations in the Rattlesnake Hills, Rawlins Uplift, and Wind River Range. They reported concentrations as great as 6,820 ppm total REEs. More recently, in mapping the bedrock geology of the Bald Mountain 7.5' quadrangle, Sell (2022) and Sell and others (2023) conducted SEM-EDS analysis of Precambrian basement and overlying Flathead Sandstone samples. Sell (2022) reported elevated REEs, particularly LREEs, in monazite and apatite grains in the Flathead Sandstone around the bases of Bald Mountain, Little Bald Mountain, and Rooster Hill, as well as on the southwest side of Duncum Mountain.

Geochemistry and Mineralogy

Forty-three samples from the Flathead Sandstone were analyzed geochemically for this study (fig. 3). The only element associated with critical or economic minerals that occurs at a median concentration above 5 times upper continental crust (UCC) abundance is silver (Ag), although these levels are many times less than that required for an economic silver deposit. A subset of samples is also enriched in REEs, particularly LREEs, as well as zirconium and hafnium. Total REE concentrations, or the sum of the lanthanides plus yttrium and scandium, averaged 898 ppm, with a range of 54.9–9,960 ppm. This is equivalent to average total rare-earth oxides (REO) of 1,050 ppm, with a range of 64.8–11,700 ppm. Most of the REE content consists of LREEs; the HREE fraction (total HREEs divided by total REEs) is only 0.077. Zirconium concentrations averaged 440 ppm, with a range of 37–2,280 ppm. Hafnium concentrations averaged 10.9 ppm, with a range of 0.9–54.1 ppm.

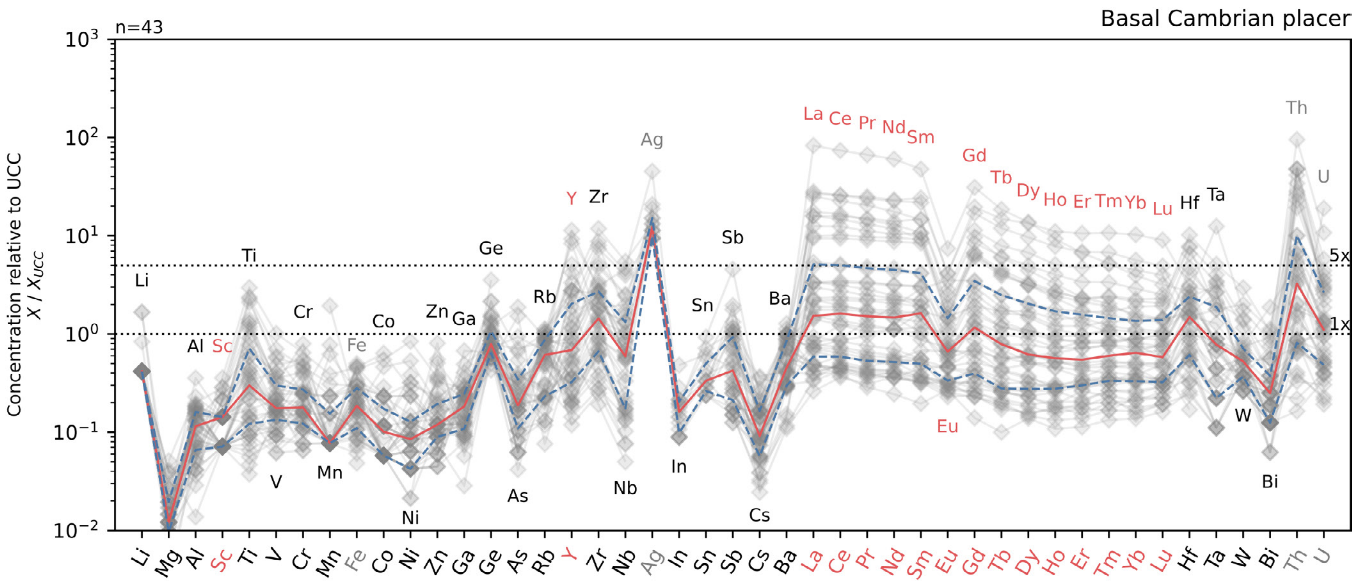

Figure 3. Concentrations relative to upper continental crust (UCC) of critical or economic elements for all Cambrian Flathead sandstone samples measured in this study. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium. The solid red line is the median, the dashed blue lines are the first and third quartiles, and n is the number of samples.

These geochemical results suggest the presence of monazite and zircon, which was confirmed by mineralogical analysis of a few select samples (figs. 4 and 5). Elevated LREE concentrations can be attributed to abundant subangular to rounded, fine- to medium-grained detrital monazite (figs. 4 and 5A). Some very fine, secondary REE-bearing phosphate was also observed (fig. 5B). A small number of HREE-bearing xenotime grains were noted as well (fig. 4). Fine-grained subrounded iron-titanium oxide grains are common (fig. 4). These typically display signs of alteration. Elongate titanium oxide, possibly secondary rutile, occurs in some pore spaces (fig. 4). Zircon grains are euhedral, elongate, and subangular to subrounded (fig. 4), but only a small number were identified, so it is likely that other morphologies exist. In addition to these placer minerals, the bulk of the basal Flathead consists mostly of subangular to subrounded quartz and potassium feldspar, ranging in size from coarse-grained sand to pebbles.

A small number of Precambrian basement samples and Quaternary alluvium samples collected near Flathead deposits were also analyzed geochemically. One sample (BM-DM-Pegmatite 1) from near Bald Mountain showed slight enrichment in HREEs, whereas another nearby sample (BM-DM-Granite K) showed slight enrichment in LREEs. Quaternary alluvium near the Bald Mountain occurrence also showed moderately elevated REE concentrations (BM-DM-Alluvium 5). In the case of Warm Spring Mountain in the Union Pass area, Quaternary alluvium (HMS-JM-20210714-4A) was more enriched in REEs than Flathead Sandstone collected nearby (HMS-JM-20210714-3ABC).

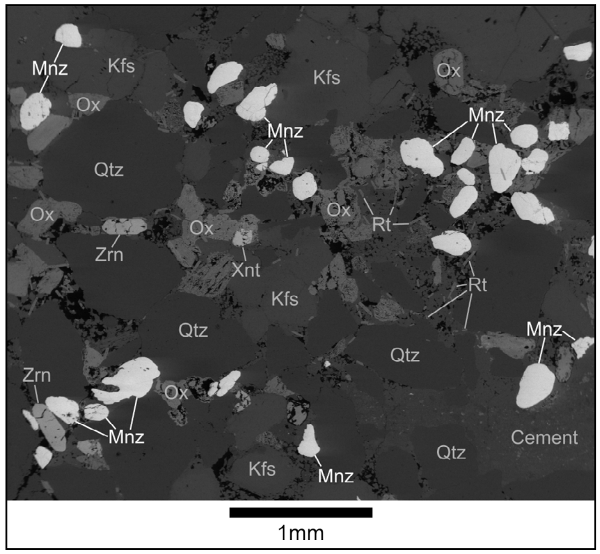

Figure 4. Annotated backscatter electron image of a heavy-mineral sandstone from the Flathead Sandstone containing abundant monazite (Mnz). Other heavy minerals in this sample include zircon (Zrn), xenotime (Xnt), elongate rutile (Rt), and Fe-Ti oxides (Ox). The light phases consist of quartz (Qtz) and K-feldspar (Kfs). Sample is HMS-DL-20220907-1A from Bald Mountain.

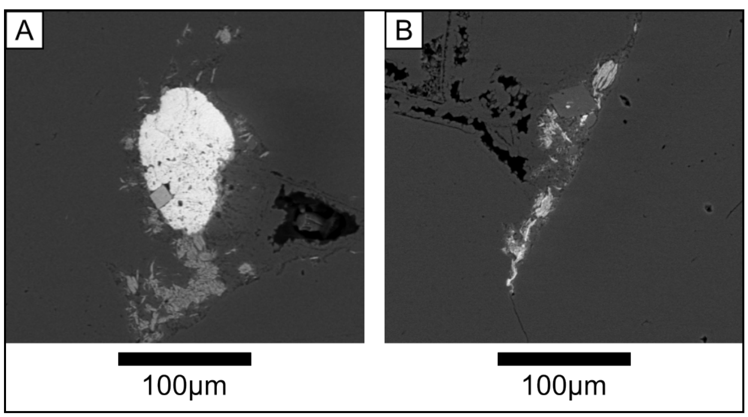

Figure 5. Backscatter electron image of LREE-phosphates from the Flathead Sandstone. A) Rounded grain of monazite (light gray) surrounded by quartz (dark gray). Medium-gray fibers are Fe-oxides or hydroxides. B) Secondary REE-phosphate (light gray) and Fe-oxides or hydroxides along boundaries between quartz grains (dark gray). Sample is HMS-DL-20220811-5A from Little Basin.

Bulk-mineral analysis (Appendix 4) of eight Flathead Sandstone samples with QEMSCAN averaged 80.2 percent quartz, with a range of 67.7 to 95.6 percent; 14.2 percent feldspar, with a range of 2.8 to 25.1 percent; 1.6 percent titanium minerals, with a range of 0.2 to 3.9 percent; and 0.8 percent "other" minerals, with a range of 0.1 to 2.4 percent. These other minerals may include trace amounts of monazite, epidote, garnets, and other unresolved mineral species.

Previously published geochemical and mineralogical datasets are summarized in the descriptions for each deposit location.

Site Descriptions

Bald Mountain, S1/2 sec. 21 and secs. 22 and 31, T. 56 N., R. 91 W., Bighorn and Sheridan counties

The Bald Mountain deposit is about 45 km east of Lovell, in the northwestern part of the Bighorn Mountains. Monazite-bearing arkosic conglomerates in the Flathead Sandstone crop out in two areas of known high enrichment. The first is along the southwest flank of Bald Mountain, about 1 km south of U.S. Highway 14A., and the second is southwest of Rooster Hill, about 1 km north of U.S. Highway 14A (fig. 6). Conglomerates with intermediate monazite enrichment exist between and around these two main areas. However, the distribution of enrichment is irregular, and the overall extent of the deposit remains somewhat poorly defined despite previous work.

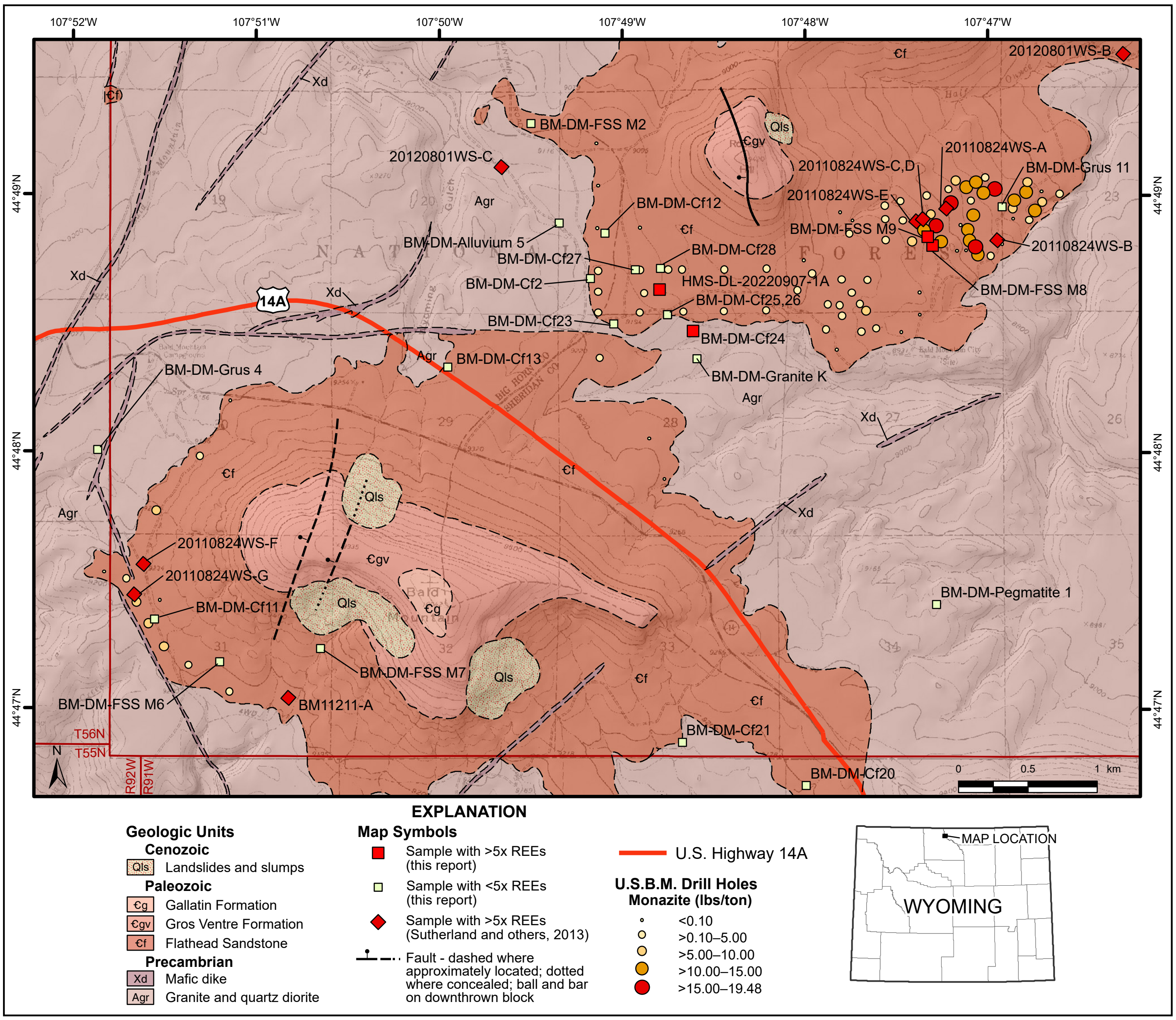

Figure 6. Map of the Bald Mountain–Rooster Hill area, showing bedrock geology, sample locations from this report and Sutherland and others (2013), and drillhole locations from McKinney and Horst (1953). Modified from fig. 41 in Sutherland and Cola (2016).

In this part of the Bighorn Mountains, relatively flat-lying Paleozoic strata rest unconformably on Archean crystalline basement. The basement rock in the Bald Mountain area is primarily a pink, coarse-grained alkali feldspar granite locally containing minor pegmatites. Recent uranium-lead zircon geochronology dates indicate a crystallization age of about 2.89 Ga (Sell, 2022). Minor outcrops of quartz monzonite ("adamellite") and a "purple granite," with similar ages to the pink alkali feldspar granite, are also described in the area (Sell, 2022; Sell and others, 2023). Younger amphibolite and diabase dikes intrude the granites (Sell, 2022). The overlying Cambrian Flathead Sandstone and Gros Ventre Formation form the core of Bald Mountain and other grassy hills that rise above subalpine rolling plains of weathered granite (fig. 7).

Figure 7. Photograph of the basal Flathead Sandstone south of Rooster Hill. In this area, the conglomerate forms a broad, gentle dipslope without overburden.

The Bald Mountain paleoplacer is restricted to the basal conglomerate of the Middle Cambrian Flathead Sandstone, which here is a pale buff-brown to maroon, poorly to well-cemented conglomerate as great as 15 m thick. The conglomerate is composed primarily of subrounded white quartzite pebbles and subangular to angular feldspar in a sand matrix (fig. 8). The quartz pebbles are thought to have originated from quartz veins in crystalline basement rock (Middleton, 1980). The basal conglomerate, which is lenticular and irregularly distributed, grades upward into the buff to pink, generally well-indurated, cross-bedded quartz arenite that comprises the bulk of the Flathead Sandstone. Monazite enrichment is generally associated with—although not limited to—the poorly cemented, deep maroon-colored conglomerate, 0.5–3 m thick, near or at the contact with the underlying crystalline basement. Monazite grains are less than 2 mm in diameter and are reddish brown in color. The zones of enrichment are also easily identified by their radioactivity, which may be as much as 20 times background levels.

Figure 8. Close-up photograph of the radioactive conglomerate at the base of the Flathead Sandstone near Bald Mountain.

Of all the fossil placers in this report, the Bald Mountain deposit has perhaps seen the most study since its discovery in the early 1900s. Initial interest in the paleoplacer was not in REE-bearing monazite but rather in gold. Gold in the Flathead at Bald Mountain occurs as flat, fine grains with jagged edges, suggesting a nearby source (Beeler, 1908; Sutherland and others, 2013). For a brief time, the gold-mining town of Bald Mountain supported about 1,500 people; however, gold concentrations (up to about 0.1 oz/ton) were not sufficient to support commercial operations, and the town was abandoned the following year (Darton, 1906; Darton and Salisbury, 1906; McKinney and Horst, 1953; Hausel, 1989).

The 1950s saw renewed interest in the Bald Mountain deposit, this time as a potential source of thorium. In the early 1950s, the U.S. Bureau of Mines (USBM) drilled 92 exploration holes and dug numerous pits and trenches at the site (Wilson, 1951; Kline and Winkel, 1952; McKinney and Horst, 1953). Drillholes were an average depth of 7 m, with a maximum depth 16 m. A total of 27 tons of drill cuttings were collected. Ore assays ranged from 2 pounds of monazite per ton up to 30 pounds per ton. McKinney and Horst (1953) described two high-grade areas.

The Rooster Hill area (E1/2 sec. 22 and center W1/2 sec. 23) contained an estimated 4,447 tons of monazite in 674,160 tons rock, averaging 13.2 pounds monazite per ton, as well as a total of 22 thousand tons of ilmenite. They also estimated an average thickness of 1.8 m for the Rooster Hill zone, which is overlain by up to 9 m of overburden. For the high-grade area along the flank of Bald Mountain (sec. 31), they reported 7,800 tons of monazite in 3.5 million tons of rock, averaging 4.45 pounds of monazite per ton. Ilmenite was also mentioned as a potential byproduct. USBM efforts to extract high-grade thorium oxide from these rock samples noted that the monazite contained 8.8 percent ThO_2, higher in thorium content than other domestic or foreign sources of monazite at the time (Borrowman and Rosenbaum, 1962). No geochemical analyses for REEs or other critical mineral commodities are known from works published by the USBM.

Since the 1950s, the sedimentological understanding of the Flathead Sandstone in Wyoming has changed. The volume estimates by McKinney and Horst (1953) assumed the sheet-like, large-lens geometry of a beach placer, but it has since been shown that the basal Flathead Sandstone is in places fluvial in origin. Middleton (1980) described a basal Flathead facies that, based on its poor sorting, coarseness, limited lateral continuity, and occasional graded bedding and cross-bedding, suggests deposition in braided streams. Although this basal facies grades upward into the transgressive shallow-marine facies assumed by McKinney and Horst (1953) in their calculations, existing data—particularly the irregular distribution of the basal conglomerate both in outcrop and in USBM drillholes—suggest that the Bald Mountain deposit, as well as other Flathead Sandstone locations described in this section, are within the fluvial facies described by Middleton (1980). King (1991) and Sutherland and others (2013) likewise remarked that the geometry of the deposit is probably far more complicated and three-dimensional than assumed by McKinney and Horst (1953). King (1991) also suggested that, because air was used in drilling, the downhole data from McKinney and Horst (1953) may not represent complete recovery of heavy minerals.

No additional published analyses of the Bald Mountain deposit are known prior to recent studies by the WSGS. Sutherland and others (2013) collected five samples east of Rooster Hill and three samples at the west end of Bald Mountain. Two of the three samples from Rooster Hill showed considerable REE enrichment: sample 20110824WS-C contained 4,715 ppm total REEs and 20110824WS-D contained 6,816 ppm total REEs. Sample 20110824WS-F from near Bald Mountain also demonstrated elevated concentrations, with 2,310 ppm total REEs. Relative to typical upper crustal abundance, enrichment in LREEs was considerably greater than in HREEs for these samples. Thorium concentrations were greatest in sample 20110824WS-D (1,110 ppm).

During mapping of the bedrock of the Bald Mountain 7.5′ quadrangle (Sell and others, 2023), Sell (2022) conducted SEM-EDS point analysis of heavy-mineral fractions in the Flathead Sandstone as well as in samples of the underlying Archean crystalline basement. Nineteen measurements of monazite from 12 samples averaged 30.24 percent cerium. Four measurements of monazite in three Flathead samples averaged 15.87 percent lanthanum, and 12 monazite measurements among eight samples averaged 11.05 percent neodymium. In Archean basement samples collected by Sell (2022), REEs were somewhat common, but not in significant quantities. REEs were relatively uncommon in sampled alluvium and grus. Sell (2022) hypothesized that, as REEs are present not only in the Flathead Sandstone but also in the crystalline basement (albeit in modest concentrations), the heavy-mineral enrichment in the Flathead Sandstone could be the result of prolonged weathering and erosion of basement rock in the greenhouse conditions of the Middle Cambrian, which formed a lag enriched in monazite, zircon, and apatite at the basal unconformity.

For this study, 27 samples of Flathead Sandstone from the northern Bighorn Mountains were analyzed, 26 of which were originally collected by Sell (2022). Eight of the samples were collected near radioactive outcrops north of U.S. Highway 14A, near Rooster Hill, that had been previously reported to contain REE enrichment. Three analyses were from the area with known enrichment south of the highway, along the southern slopes of Bald Mountain. Sixteen additional samples were from Flathead Sandstone outcrops for which the critical mineral content was unknown. These "background" samples were mostly collected in the vicinity of Bald Mountain and Rooster Hill, but a few were from elsewhere in the northern Bighorn Mountains. Some weathered and unweathered Precambrian basement samples were also collected from the area.

A wide range of concentrations were measured in the deposit north of Bald Mountain near Rooster Hill (fig. 9). REEs and thorium were elevated in several samples (HMS-DL-20220907-1A, BM-DM-FSS M8, BM-DM-Cf24, BM-DM-FSS M9). However, many samples in the area did not show significantly elevated REE concentrations, supporting the idea that the geometry of the Bald Mountain deposit is more complex than the uniform sheet assumed by McKinney and Horst (1953). Total REEs at the northern location ranged from 64.9 ppm to 9,960 ppm, with an average of 1,640 ppm. The sample with the greatest REE concentrations (HMS-DL-20220907-1A) was collected from the southwestern extent of the known deposit near Rooster Hill, where USBM drillholes had previously shown only slight enrichment in monazite (McKinney and Horst, 1953).

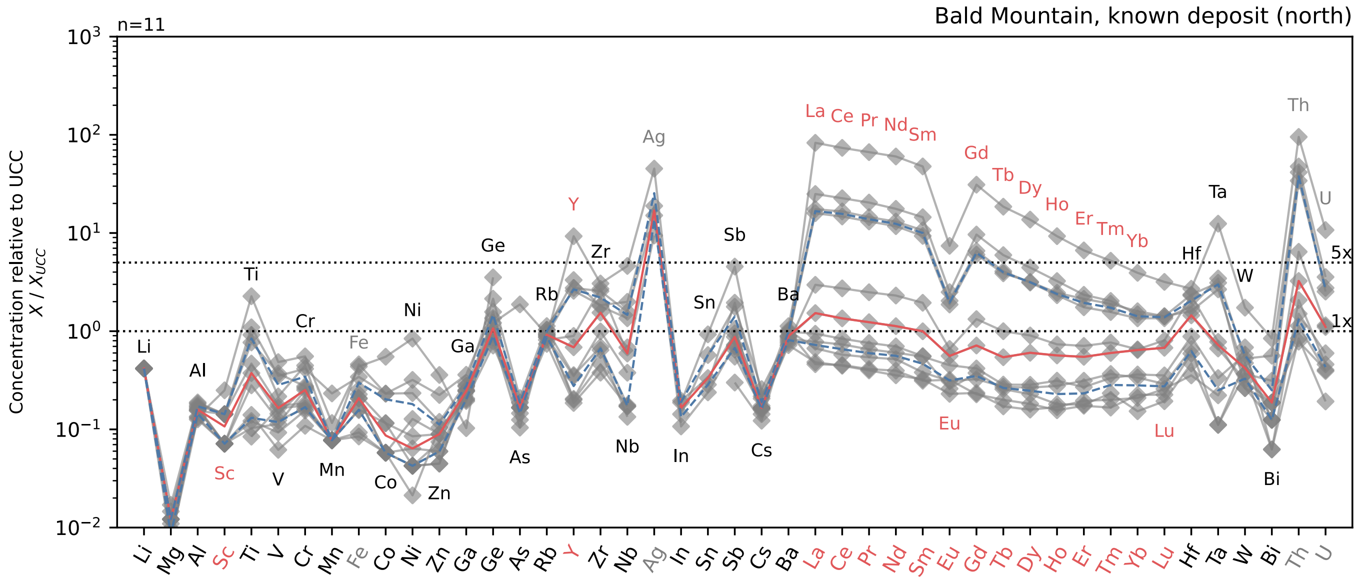

Figure 9. Concentrations relative to upper continental crust (UCC) of critical or economic elements for Cambrian Flathead Sandstone samples collected from the northern segment of the known deposit at Bald Mountain, near Rooster Hill. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium. The solid red line is the median, the dashed blue lines are the first and third quartiles, and n is the number of samples.

South of U.S. Highway 14A, REE concentrations were less than expected (fig. 10). Although the Flathead Sandstone is close to the surface along the flanks of Bald Mountain, widespread colluvium and alluvium make surface sample collection difficult in this area. Total REE concentrations ranged from 181 ppm to just 443 ppm, with an average of 287 ppm. These measurements are far less than the total REEs of 2,310 ppm reported by Sutherland and others (2013) in the same area (sample 20110824WS-F).

All of the “background” samples collected in the area showed low concentrations of elements associated with critical and economic minerals, except for a small number that were slightly enriched in thorium, zirconium, and hafnium (fig. 11).

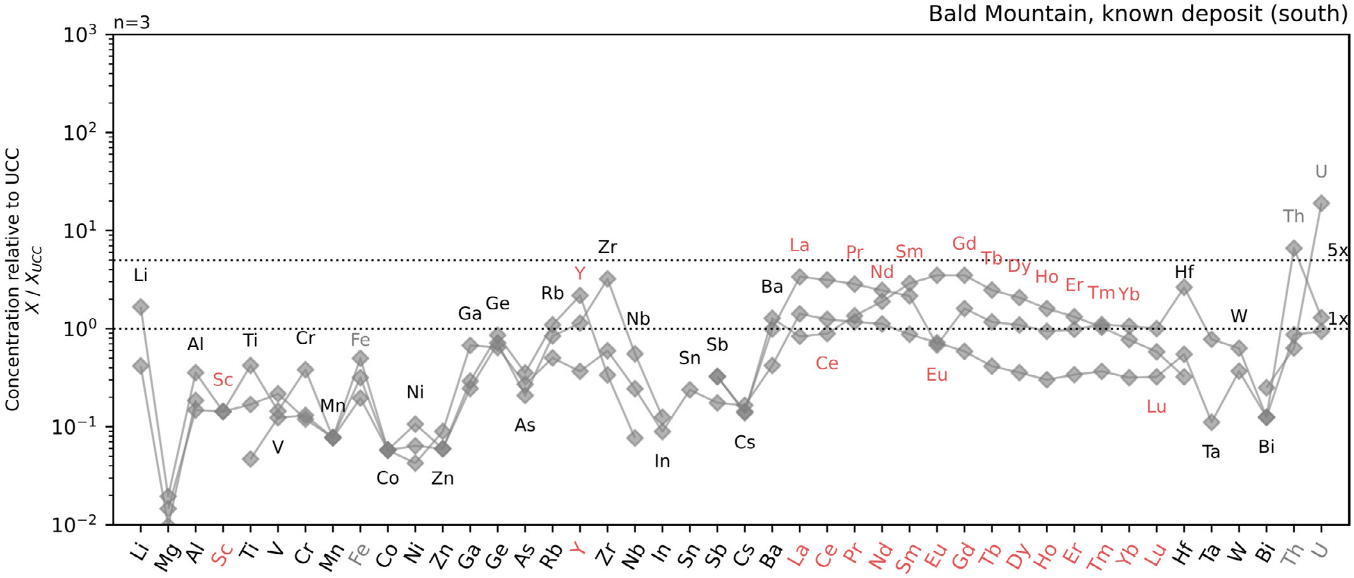

Figure 10. Concentrations relative to upper continental crust (UCC) of critical or economic elements for Cambrian Flathead Sandstone samples collected from the southern segment of the known deposit at Bald Mountain. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium, and n is the number of samples.

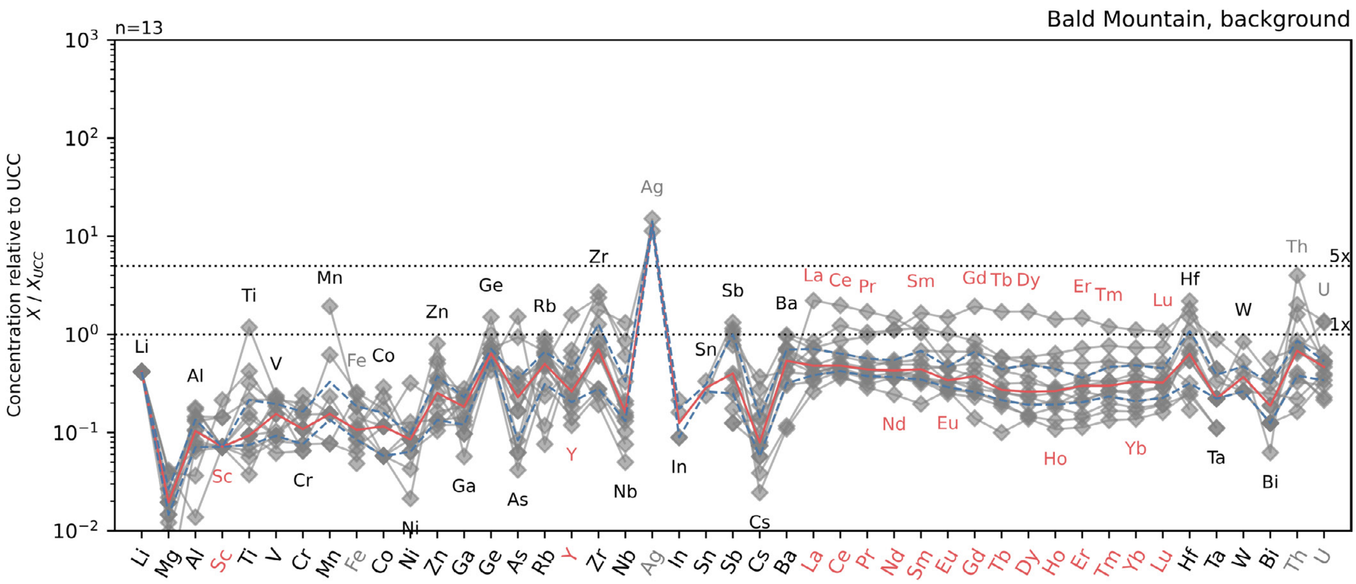

Figure 11. Concentrations relative to upper continental crust (UCC) of critical or economic elements for Cambrian Flathead Sandstone samples collected outside the known area of REE-enrichment at Bald Mountain. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium. The solid red line is the median, the dashed blue lines are the first and third quartiles, and n is the number of samples.

Prospect Creek area, SW1/4 NW1/4 sec. 26, T. 48 N., R. 86 W., Washakie County

The Prospect Creek location is 25 km east of the town of Tensleep, in the southern Bighorn Mountains. The outcrop is 5.5 km south of U.S. Highway 16 and 24 km west of the T-junction where U.S. Forest Service (USFS) Road 25 ends. The basal Flathead Sandstone crops out in a stand of aspen trees (fig. 12) less than 200 m west of the Prospect Creek drainage, 650 m north of USFS Road 8020. Exposure is sporadic, and the radioactive conglomerate was observed for a distance of less than 30 m. The actual dimensions of the deposit are unknown.

The Middle Cambrian Flathead Sandstone at this location lies unconformably on Precambrian crystalline basement that differs from the granitic rocks near Bald Mountain in the northern part of the range. In the southern Bighorn Mountains, the basement rock is predominantly quartzofeldspathic gneiss with a metamorphism age of about 2.8 Ga (Stueber and Heimlich, 1977).

Figure 12. Photograph of the basal Flathead Sandstone at Prospect Creek.

Like at other Cambrian paleoplacer locations, the basal conglomerate of the Flathead at Prospect Creek grades upward into cross-bedded quartz arenite. Strata here dip gently to the west. The base of the conglomerate is very poorly exposed, and its thickness is unknown, although probably less than 1 m. Lithologically, the deposit is similar to that at Bald Mountain. The radioactive zone was limited to the lowermost 0.5 m of the outcrop. Radioactivity measured 3 to 8 times background levels.

Wilson (1960) first noted anomalous radioactivity in this area. Damp and others (1982) collected one sample (MLK-47) near this location that they described as a thorium-bearing sandstone. They reported geochemical results of 215 ppm lanthanum, 40 ppm yttrium, 11,100 ppm titanium, 1,650 ppm zirconium, 366 ppm equivalent thorium, and 18 ppm equivalent uranium. Sutherland and Cola (2016) collected a quartz-pebble conglomerate from the Flathead about 2.3 km east of this location (20150810LC-6), but their geochemical analysis did not reveal any enrichment in REEs or other elements of interest.

For this study, two samples were collected and analyzed. Both samples were moderately enriched in REEs and thorium, with total REE concentrations ranging from 707 ppm to 719 ppm, and thorium ranging from 105 ppm to 106 ppm. One of the samples also contained 1,540 ppm zirconium and 40.2 ppm hafnium. All detected elements associated with critical and economic minerals at the Prospect Creek location are shown in fig. 13.

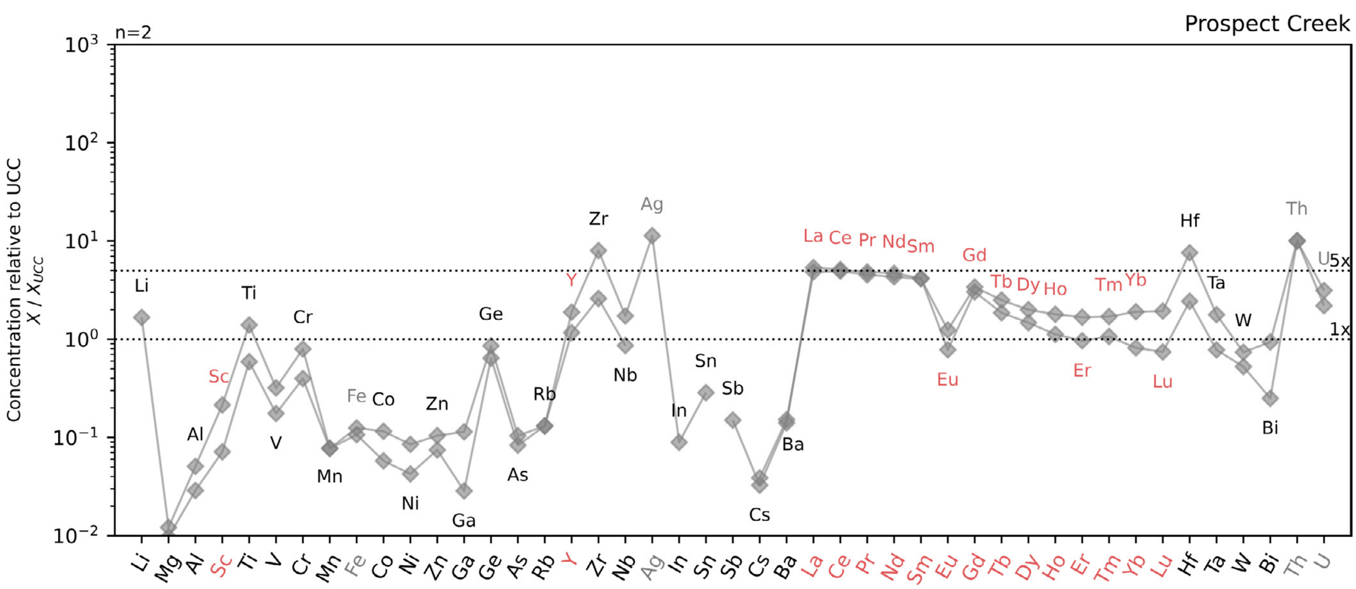

Figure 13. Concentrations relative to upper continental crust (UCC) of critical or economic elements for Cambrian Flathead Sandstone samples collected at the Prospect Creek location. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium, and n is the number of samples.

Bear Gulch, center W1/2 sec. 18, T. 47 N., R. 85 W., Johnson County

About 8 km south-southeast of the Prospect Creek deposit, near the upstream extent of Bear Gulch, Damp and Brown (1982) collected and analyzed one Flathead Sandstone sample (MJG-243). The outcrop is near the top of a hill 0.8 km west of Gold Mine Road (USFS Road 452) on private land. Damp and Brown (1982) described a quartz-pebble conglomerate, yellow and medium grained, that contained 324 ppm equivalent thorium, 8,650 ppm titanium, 2,650 ppm zirconium, less than 100 ppm lanthanum, and less than 40 ppm yttrium. The elevated thorium, titanium, and zirconium concentrations suggest this is a paleoplacer similar to that at nearby Prospect Creek. Although sample MJG-243 did not exhibit significant REE enrichment, King (1991) suggested that REEs might be elevated in other parts of this outcrop. The exact extent of this potential deposit or the nature of its relationship to the Prospect Creek deposit are unknown. The Bear Gulch location was not visited for this study.

Oakie Trail, S½NE¼ sec. 15, T. 40 N., R. 88 W., Natrona County

The Oakie Trail location is 17 km east of Nowood Road (County Road 82) near the southern end of the Bighorn Mountains. Malan (1972) reported that a conglomerate in the Flathead Sandstone at this location contained up to 134 ppm thorium. Sutherland and others (2013) described this outcrop as consisting of reddish quartz-pebble conglomerate and subarkosic sandstone. They collected and analyzed two samples (20121017JC-E, F), which contained only 3.89–24 ppm thorium and were otherwise unremarkable. However, based on the elevated thorium concentrations reported by Malan (1972), it is possible that other parts of this outcrop may be enriched in REEs. The Oakie Trail location was not visited for this study.

Western Rattlesnake Hills, SE1/4 NE¼ sec. 16, T. 32 N., R. 88 W., Natrona County

A radioactive outcrop of the basal Flathead Sandstone is enriched in REEs at this location, which is about 80 km west of Casper and 88 km east of Riverton, in the western Rattlesnake Hills. The outcrop is situated 100 m east of Dry Creek Road (County Road 321), about 32 km north-northwest of the intersection of Dry Creek Road with Wyo. Highway 220.

The deposit is in a tan to pink conglomerate near the base of the Flathead Sandstone (figs. 14 and 15). Strata here dip about 20 degrees to the northeast. The crystalline basement rock in the region, which is obscured by alluvium and colluvium in the immediate vicinity, consists of a complex assortment of Proterozoic and Archean intrusive rocks, Archean metasedimentary and metaigneous rocks of the Rattlesnake Hills greenstone belt, and the Paleoarchean basement gneiss complex (Sutherland and Hausel, 2005).

No published references to this deposit are known prior to Sutherland and Cola (2016). In addition to the enrichment at the base of the Flathead (sample 20110429BG-A in Sutherland and Cola, 2016), REEs are also elevated in a reddish conglomerate 1.5 m upsection from the base (20110429BG-B) and in a dark-purple conglomerate (20110429BG-C) immediately upsection of the reddish conglomerate. Sutherland and Cola (2016) measured an average of 950 ppm total REEs in their samples from this location, with a maximum of 1,176 ppm total REEs (sample 20110429BG-B).

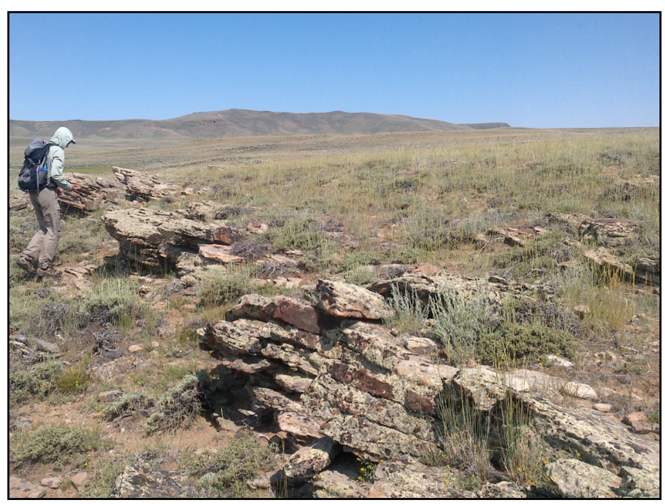

Figure 14. Photograph of Flathead Sandstone at the western Rattlesnake Hills location.

In our visit to this outcrop, we measured 2–7 times background levels of radiation, with the greatest levels at the reddish conglomerate bed (fig. 15). Elevated radiation levels were observed for a distance of about 175 m along the outcrop. We also measured slightly radioactive (2–3 times background) cross-bedded quartz arenite sandstone about 5 m upsection of the conglomerates. Because of poor exposure, the actual dimensions of this deposit are unknown. Two old prospect trenches had been dug into the quartz arenite at the top of the hill, although neither was deep enough to reach the radioactive conglomerate horizons. No samples from this location were analyzed for this study.

In the eastern Rattlesnake Hills, about 18 km east of the western Rattlesnake Hills location, Sutherland and others (2013) analyzed another sample from the Flathead Sandstone (SR7-30-10-A). They observed no significant enrichment in critical minerals.

Figure 15. Close-up photograph of radioactive, red-stained basal Flathead conglomerate at the western Rattlesnake Hills location.

Little Basin area, NW1/4NW1/4 sec. 27 and SW1/4SW1/4 sec. 22, T. 29 N., R. 83 W., Natrona County

The Little Basin deposit is about 10 km south of Alcova and 6.5 km east of Pathfinder dam, at the northeastern edge of the Granite Mountains. The outcrop is 1 km south of Fremont Canyon Road (County Road 408), 2.1 km west of its intersection with Kortes Road (County Road 407).

The paleoplacer at Little Basin immediately overlies crystalline basement, which in this area consists of Neoarchean granite of the Wyoming batholith, as well as some diabase dike intrusions (Jones and Gregory, 2011). Because of poor exposure, the thickness of the basal conglomerate here is unknown, but likely less than about 1–1.5 m. The strata dip about 7 degrees to the northeast. We observed radioactive zones sporadically over a distance of 350 m along the outcrop. These zones were generally less than 0.3 m thick. Radioactivity ranged from 3 to 15 times background levels. The enrichment occurs in a cross-bedded, texturally immature, arkosic, dark-maroon-stained pebble conglomerate and coarse sandstone near the base of the formation (fig. 16).

Figure 16. Photograph of the basal Flathead Sandstone at the Little Basin deposit.

It is uncertain if this deposit is actually in the basal Flathead Sandstone. Sando and Sandberg (1987) argued that the sandstone unit that overlies crystalline basement at nearby Fremont Canyon and in the northern Laramie Range is actually Devonian in age. However, because later geologic mapping in the region classifies this lowermost Paleozoic unit as either undivided Devonian Fremont Canyon Sandstone and Cambrian Flathead Sandstone (Dixon, 1990), or simply Cambrian Flathead Sandstone (Jones and Gregory, 2011), and because of the similarity of the Little Basin conglomerate to basal Flathead facies described by Middleton (1980), we grouped this deposit with other Cambrian Flathead Sandstone paleoplacers.

At Little Basin, Griffin and others (1982) collected three samples (MFB-226–228) of weathered Flathead conglomerate, which exhibited a range of thorium concentrations, from 783 to 10,300 equivalent thorium. No other geochemical measurements were made, although they also conducted two heavy-mineral analyses. The heavy-mineral fraction of sample MFB-226 contained 68 percent monazite, 17 percent zircon, and 12 percent limonite, with trace amounts of hematite and rock fragments. The heavy minerals in sample MFB-227, which totaled greater than 100 percent in the original dataset, comprised 64 percent limonite, 43 percent monazite, 10 percent rock fragments, 1 percent xenotime, 1 percent ilmenite, and trace biotite, chlorite, rutile, tourmaline, and zircon. To the northwest, in sec. 21, Malan (1972) measured somewhat elevated thorium concentrations, suggesting a lower grade deposit may extend beyond the outcrop described by Griffin and others (1982).

For this study, four samples were collected and geochemically analyzed. Total REE concentrations ranged from 1,750 ppm to 3,820 ppm, with an average of 2,880 ppm. In addition to fine-grained detrital monazite, examination of a thin section created from one of these samples revealed the presence of a small amount of secondary REE-bearing phosphate. All detected elements associated with critical and economic minerals at the Little Basin location are shown in fig. 17.

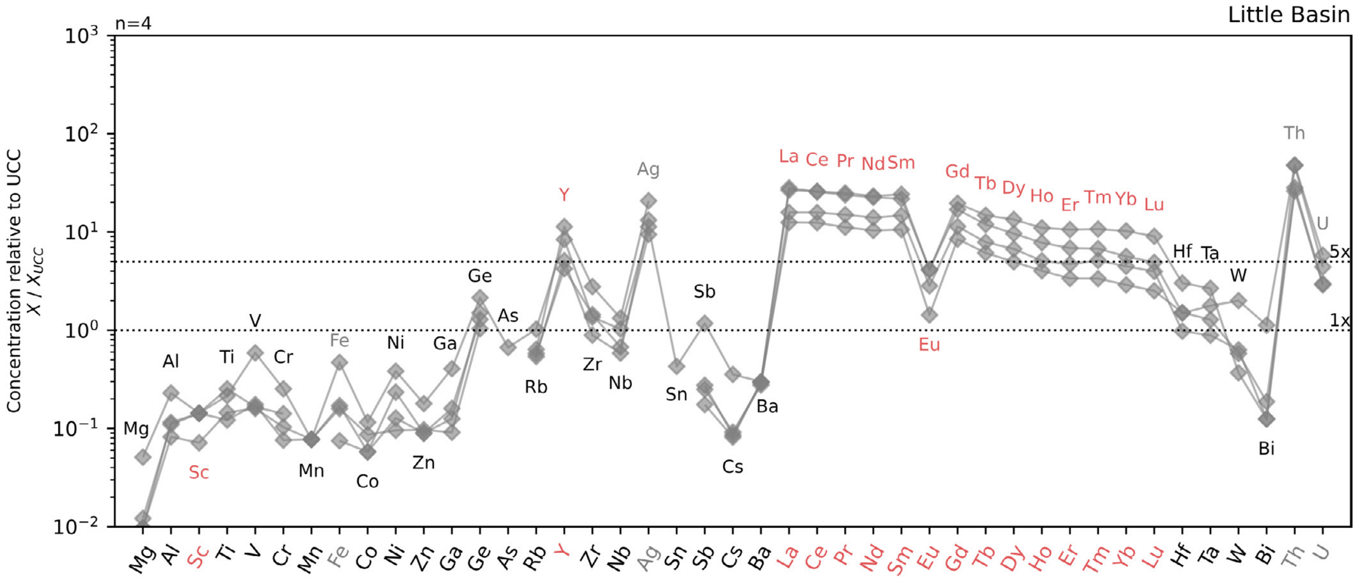

Figure 17. Concentrations relative to upper continental crust (UCC) of critical or economic elements for Cambrian Flathead Sandstone samples collected at the Little Basin location. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium, and n is the number of samples.

Rawlins Red, sec. 8, T. 21 N., R. 87 W., Carbon County

In the late 1800s, Rawlins Red hematite ore was used as a metallurgical flux and as paint pigment. Trace gold was also reported, a claim that caused controversy at the time. Hausel and others (1992, 1994) later confirmed that gold was present in the Flathead Sandstone here, but in small quantities and with irregular distribution. Hausel and others (1992, 1994) and Sutherland and Cola (2015) also observed elevated REEs in arkosic sandstones and conglomerates associated with the hematite ore.

The Rawlins Red deposit is about 3 km north of the center of Rawlins, less than 1.5 km west of U.S. Highway 287, where the Flathead Sandstone crops out on the southeastern flank of the Rawlins Uplift. The iron ore consists of hematitic conglomerate and massive hematite that contains up to 65 percent iron. Arkosic conglomerates with less iron content also crop out along the north edge of town.

Hausel and others (1992, 1994) reported geochemical analyses for 13 samples from arkosic conglomerate, hematitic conglomerate, and massive hematite at and surrounding the Rawlins Red deposit. Most of the samples did not contain elevated precious metals or critical minerals. Sample RA1-91, a panned concentrate from the hematitic conglomerate, contained 2.4 ppm gold. Arkosic conglomerate samples RA15-91 and RA16-91 were collected in the SE1/4SW1/4 of sec. 8., about 1 km south-southwest of the more well-known hematitic ore body. Both contained somewhat elevated total REE concentrations of 518 ppm and 686 ppm, respectively, not including scandium or yttrium. Lanthanum and cerium concentrations were about 4–5 times upper crustal abundance. The samples were not measurably radioactive.

Sutherland and Cola (2015) published the results of four geochemical analyses of the Rawlins Red deposit. One of these samples (CC134), collected in NE1/4 of sec. 8, was a red to brown, fine- to medium-grained, arkosic sandstone that contained LREEs and strontium in concentrations greater than five times upper crustal abundance. Total REEs in this sample measured 1,642 ppm. The sample also contained 30.8 percent iron.

Overall, the Rawlins Red occurrence appears to be another low-grade paleoplacer in the basal Flathead Sandstone. Most previously published work on this location has focused on gold and iron. Data on REEs are limited to analyses of a few grab samples, and a thorough geochemical dataset does not exist. The Rawlins Red location was not visited for this study.

Meadow Gulch, SW1/4 sec. 29, T. 30 N., R. 99 W., Fremont County

The Meadow Gulch deposit (site 6-8 in King [1991]; unnamed in Sutherland and Cola [2016]) is 32 km south of Lander, about 3 km east of the Atlantic City Iron Mine. The outcrop (fig. 18) is along USFS Road 323, 2.5 km east of the Wyoming Department of Transportation maintenance location near the intersection of Dickinson Avenue and Atlantic City Road. The basal Flathead Sandstone crops out 100 m north of the road, beyond a stand of aspen and pine trees near the upstream extent of Meadow Gulch. Upsection and to the northeast, Mississippian Madison Limestone caps cliffs of Paleozoic strata that overlook Beaver Creek. The basement rock immediately underlying the Meadow Gulch deposit and exposed to the west is the Archean Roundtop Mountain Greenstone, which is composed of greenschist- to amphibolite-grade metamorphosed basalts and volcanogenic metasedimentary rocks intruded by mafic dikes (Hausel, 2006). Near the eastern extent of the Meadow Gulch Flathead outcrop, the crystalline basement consists of the Archean Miners Delight Formation, which in the immediate vicinity is predominantly meta-andesite with some metadacite and metagraywacke (Hausel, 2006).

The basal Flathead outcrop at Meadow Gulch trends roughly northeast along the drainage for a distance of about 1.5 km with variable exposure quality. The actual dimensions of the deposit are unknown. Sporadic radioactive zones were observed for a total length of 400 m. Radioactive reddish quartz-pebble conglomerates of unknown thickness, often obscured by colluvium and alluvium, occur at the base of the outcrop. Radioactivity ranged from 2 to 5 times background levels. The basal conglomerate grades upward into the hard cross-bedded quartz arenite typical of the Flathead Sandstone in the area (Middleton, 1980).

Figure 18. Photograph of the Flathead Sandstone near Meadow Gulch.

At this location, Gebhardt and others (1982) collected one sample (MJF-062) in which they measured 312 ppm equivalent thorium, 17 ppm equivalent uranium, and 20 ppm chemical U_3O_8. No other geochemical analyses or other data were provided. They also reported 200 ppm equivalent thorium in the Flathead Sandstone about 3 km southeast of Meadow Gulch, in sample MJF-063, which suggests low-grade heavy-mineral enrichment might be present elsewhere in the area.

For this study, five samples from the Meadow Gulch location were geochemically analyzed. All but one of the samples were slightly to moderately enriched in zirconium, LREEs, hafnium, and thorium. Zirconium concentrations ranged from 177 ppm to 2,280 ppm, with an average of 1,300 ppm. Total REE concentrations ranged from 101 ppm to 1,440 ppm, with an average of 743 ppm. Hafnium levels ranged from 4.65 ppm to 54.1 ppm, with an average of 31.4 ppm. Thorium levels ranged from 9.12 ppm to 241 ppm, with an average of 118 ppm. All detected elements associated with critical and economic minerals at the Meadow Gulch location are shown in fig. 19.

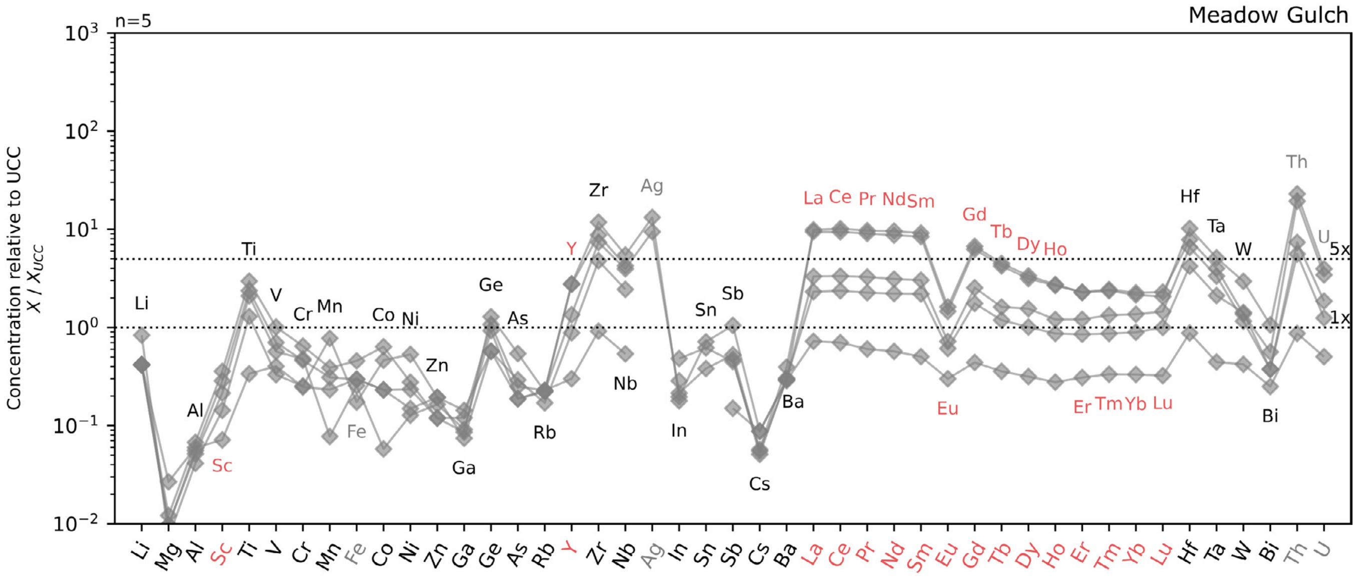

Figure 19. Concentrations relative to upper continental crust (UCC) of critical or economic elements for Cambrian Flathead Sandstone samples collected at the Meadow Gulch location. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium, and n is the number of samples.

Sinks Canyon, SE1/4 sec. 23, SW1/4 sec. 26, and possibly SE1/4 sec. 22, T. 32 N., R. 101 W., Fremont County

Another potential paleoplacer in the basal Flathead Sandstone for which there is very little previously published data is in Sinks Canyon, where the Flathead Sandstone crops out about 0.8 km upstream of where Louis Lake Road (USFS Road 300) ascends the switchbacks up the south rim. Sporadic Flathead exposure (fig. 20) continues to the south, where densely treed outcrops overlook the east end of Frye Lake. The underlying basement rock in the area is Archean biotite quartz monzonite of the Bears Ear pluton and quartz diorite of the Louis Lake batholith (Johnson and Sutherland, 2009). As for other Cambrian occurrences described in this report, the basal Flathead conglomerate here is a poorly exposed buff to reddish conglomerate, locally radioactive, that unconformably overlies crystalline basement.

The only known published data for this paleoplacer consist of a few NURE analyses by Gebhardt and others (1982). Sample MJF-022, collected about 0.5 km west of the Louis Lake Road switchbacks, on the north wall of the canyon in sec. 23, is their only sample that strongly implied paleoplacer enrichment, containing 446 ppm equivalent thorium, 21 ppm equivalent uranium, and 23 ppm chemical U_3O_8. MJF-023, collected at the same location, showed no thorium or uranium enrichment. No data were reported for MFJ-056 and MFJ-112, also

Figure 20. Photograph of small outcrop of basal conglomerate of the Flathead Sandstone near Frye Lake south of Sinks Canyon.

collected on the north side of the canyon, except that MFJ-056 contained 14 ppm chemical U_3O_8. MFJ-055, collected about 1 km to south on the northeastern shore of Frye Lake, contained 74 ppm equivalent thorium.

For this study, three conglomerate samples were collected east of Frye Lake in sec. 26, where radioactivity levels of 2 to 4 times background were observed. One sample of slightly radioactive float was also collected from the base of the north wall of Sinks Canyon in sec. 23.

All analyses revealed slightly to moderately elevated zirconium, LREEs, hafnium, and thorium concentrations. Zirconium concentrations ranged from 257 ppm to 993 ppm, with an average of 509 ppm. Total REE concentrations ranged from 252 ppm to 488 ppm, with an average of 330 ppm. Hafnium levels ranged from 5.88 ppm to 25 ppm, with an average of 12.7 ppm. Thorium levels ranged from 35.8 ppm to 54.8 ppm, with an average of 44.1 ppm. All detected elements associated with critical and economic minerals in the Sinks Canyon area are shown in fig. 21.

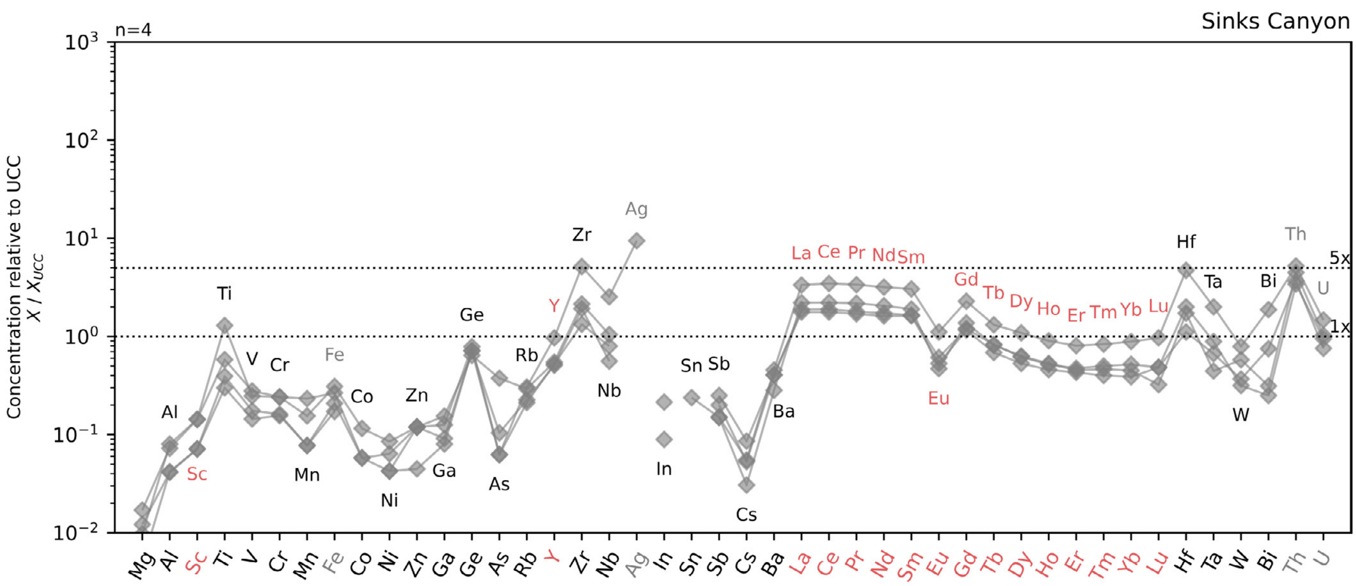

Figure 21. Concentrations relative to upper continental crust (UCC) of critical or economic elements for Cambrian Flathead Sandstone samples collected in the Sinks Canyon–Frye Lake area. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium, and n is the number of samples.

Freak Mountains, NW1/4 SW1/4 sec. 28, T. 31 N., R. 100 W., Fremont County

Little is known about the potential paleoplacer in the Flathead Sandstone in the Freak Mountains, located on the eastern flank of the Wind River Range, about 22 km south of Lander. The outcrop is 0.5 km south of USFS Road 352, along the northern bank of the Little Popo Agie River. Geologic mapping at 1:100,000 scale indicates the outcrop is likely composed of basal Flathead conglomerate (Johnson and Sutherland, 2009). The underlying basement rock is predominantly Archean quartz diorite of the Louis Lake batholith.

Gebhardt and others (1982) collected two samples near here, MFJ-116 and MFJ-171. They reported the results of geochemical analysis for just MFJ-171, which contained 237.5 equivalent thorium, 10.2 equivalent uranium, and 13 chemical U_3O_8. Perhaps because the thorium enrichment in this sample is modest, neither King (1991) nor Sutherland and Cola (2016) referenced this outcrop in their lists of potential REE deposits; however, we suspect this location is related to paleoplacers in the Flathead Sandstone found elsewhere in the region. The significance of this occurrence is uncertain, its extent is unknown, and its geologic context remains unverified. The Freak Mountains location was not visited for this study.

Mosquito Park, sec. 24, T. 2 S., R. 3 W. (Wind River Meridian), Fremont County

A conglomerate in the Flathead at this location was reported to contain 366 ppm thorium and 11 ppm uranium (Malan, 1972). The outcrop is along Moccasin Lake Road near Mosquito Park, on the Wind River Indian Reservation. No additional published information is known about this potential deposit. King (1991) suggested that this is a paleoplacer based on the thorium content. The Mosquito Park location is an unverified radioactive conglomerate in the Flathead Sandstone and therefore a potential occurrence of REEs and other critical minerals. The Mosquito Park location was not visited for this study.

Warm Spring Mountain, SE1/4 sec. 34, T. 42 N., R. 108 W., possibly sec. 31, T. 42 N., R. 108 W., Fremont County

This general location encompasses the Union Pass-Warm Spring area, where the northern Wind River Range meets the southern Absaroka Range. Because Quaternary placers are known along Warm Spring Creek, Sutherland and Cola (2016) hypothesized that heavy-mineral enrichment may also be present in the Flathead Sandstone here as well.

The Flathead in this area crops out sporadically along Warm Spring Creek and the flanks of Warm Spring Mountain. The outcrops are predominantly of cross-bedded quartz arenite. The basement rock in the area is likely Archean gneiss and migmatite (Sims and others, 2001), although no detailed map of Precambrian rocks in the immediate vicinity is known. The contact between the crystalline basement and the Flathead Sandstone in this area is often covered by colluvium, talus, or the Eocene Wind River Formation (Rohrer, 1968). It is unclear if the basal conglomerate facies of the Flathead is covered or simply not present at this location. Middleton (1980) did not mention basal arkose-conglomerate in the Flathead Sandstone near the confluence of the north and south forks of Warm Springs Creek, near the sample location for 20110920WS-A from Sutherland and Cola (2016). Middleton (1980) did, however, describe basal conglomerate at a small number of locations in the northwestern part of the state, at outcrops in Teton Canyon and at Beartooth Butte (Middleton, 1980).

Sutherland and others (2013) collected two samples from the Flathead in the Union Pass-Warm Spring area. They measured only slightly elevated thorium (19.9 ppm) in sample 20110920WS-A and no enrichment in REEs or other elements of interest. Sample 20121004JC-C was likewise unremarkable.

We revisited the area for this study. No radioactive conglomerates were observed near the confluence of Trappers Creek and Warm Spring Creek or near the confluence of the north and south forks of Warm Spring Creek, along USFS Road 532. Slightly radioactive (about 2–3 times background) medium- to coarse-grained quartz sandstone was observed along the southwestern flank of Warm Spring Mountain, in SE1/4 sec. 34, T. 42 N., R. 108 W. (fig. 22). Sample HMS-JM-20210714-3ABC from this outcrop contained 202 ppm total REEs, 18.2 ppm thorium, 656 ppm zirconium, and 16.4 ppm hafnium (fig. 23). The somewhat elevated zirconium content suggests this could be a very low-grade placer, perhaps a beach placer in the middle part of the Flathead Sandstone. In contrast, Quaternary alluvium collected along Warm Spring Creek (sample HMS-JM-20210714-4A) was more enriched in REEs than the Flathead Sandstone samples (fig. 24).

Figure 22. Photograph of slightly radioactive coarse-grained sandstone near Warm Spring Mountain.

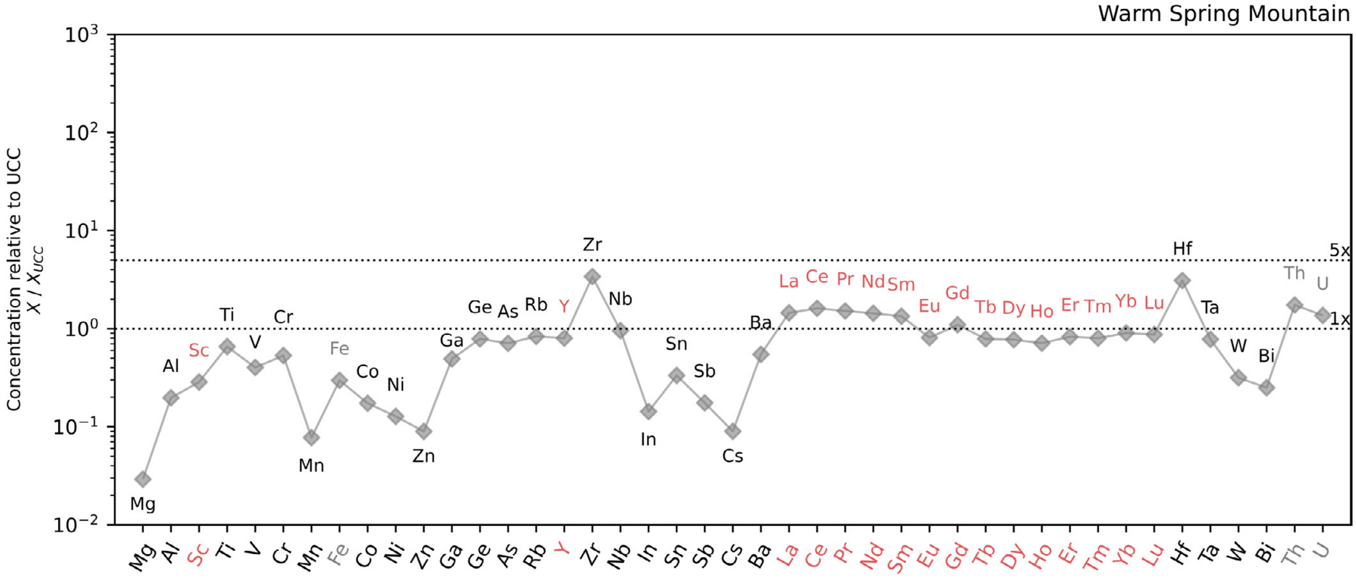

Figure 23. Concentrations relative to upper continental crust (UCC) of critical or economic elements for sample HMS-JM-20210714-3ABC of the Flathead Sandstone samples from the Warm Spring Mountain location. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium.

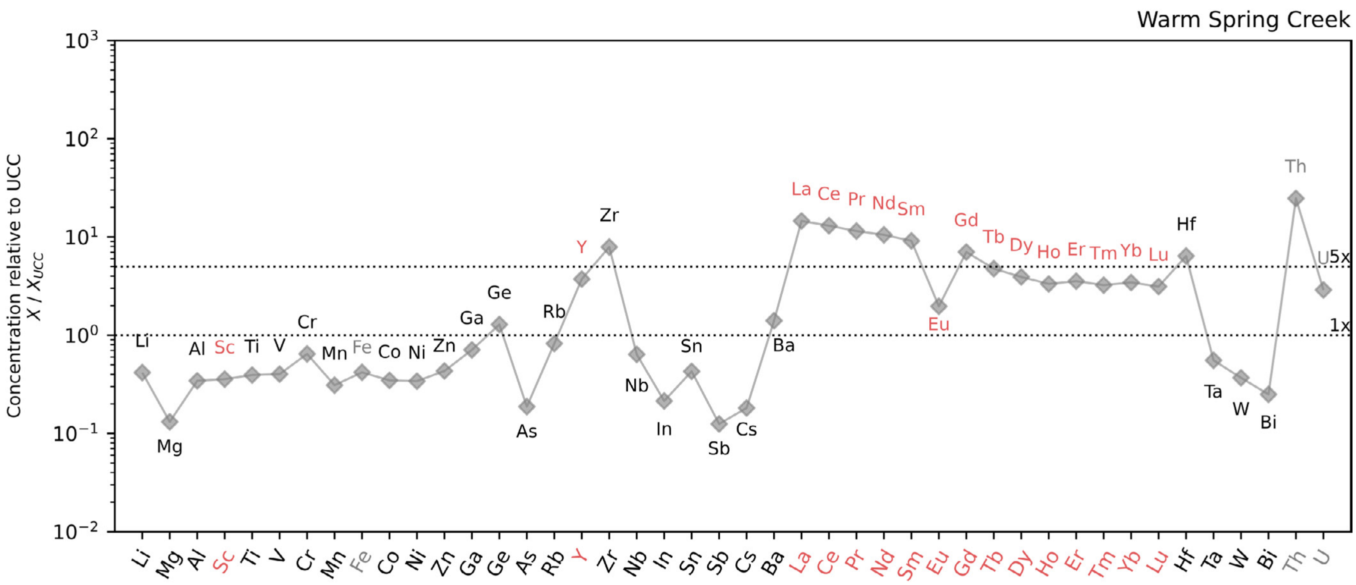

Figure 24. Concentrations relative to upper continental crust (UCC) of critical or economic elements for sample HMS-JM-20210714-4A of Quaternary alluvium from alongside Warm Spring Creek. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium.

Shoshone Canyon, roughly center sec. 6, T. 52 N., R. 102 W., Park County

Garrand and others (1982) collected a sample of Flathead Sandstone (MFO-227) at this location, about 10 km west of Cody along U.S. Highway 14/20. The outcrop is near the road immediately east of the first tunnel near Buffalo Bill dam. Garrand and others (1982) described this sample as being from a 0.6-m-thick channel in the Flathead Sandstone, which here dips about 10 degrees to the east. The exact stratigraphic location of the sample within the Flathead Sandstone is unclear. Middleton (1980) examined Flathead outcrop about 1.5 km to the west of here and omitted any mention of basal conglomerate. Garrand and others (1982) reported radioactivity of about 3 to 4 times background at the sample location, but they also reported similar measurements for the underlying Precambrian granite and the overlying Gros Ventre Shale. The Precambrian basement, which here is composed of predominantly Archean granitic rocks (Pierce, 1966; Sims and others, 2001), exhibited radioactivity as high as 9 times background levels.

Semi-quantitative analysis by Garrand and others (1982) showed that sample MFO-227 contained 10,000 ppm titanium, 700 ppm zirconium, 150 ppm lanthanum, 30 ppm yttrium, and 2 ppm gold. Because this sample displayed elevated titanium and gold, and because the outcrop was radioactive yet only contained 5 ppm chemical U_3O_8 (no measurement for thorium was made), King (1991) suggested that REEs could be elevated elsewhere at this outcrop. King (1991) also briefly mentioned at least four other possible paleoplacer occurrences in the Flathead Sandstone in northwestern Wyoming; these are described in this report's "Sunlight Basin area" section. The Shoshone Canyon location was not visited for this study.

Sunlight Basin area, SW1/4 sec. 6 and sec. 8, T. 55 N., R. 104 W.; sec. 8 and SW1/4 sec. 19, T. 56 N., R. 104 W.; and SW1/4 sec. 16, T. 57 N., R. 103 W., Park County

Several potential paleoplacers exist in the Flathead Sandstone in the Sunlight Basin area in northwestern Wyoming. Previously published data on these locations are scarce, and those data that do exist are somewhat puzzling. Five outcrops are described or mentioned by Garrand and others (1982), all roughly 40 km north-northwest of Cody. The sites occur along the southeastern margin of the Beartooth Mountains Uplift, from near the intersection of Wyo. Highway 296 (Chief Joseph Highway) with USFS Road 101 (Sunlight Road) to near the mouth of Clarks Fork Canyon, about 13 km to the northeast. No analyses for thorium exist at these locations, and REE data are incomplete, but King (1991) suggested these may be paleoplacers. However, descriptions by Garrand and others (1982) for a few of the locations differed somewhat from radioactive basal Flathead arkose-conglomerates observed elsewhere. In particular, in several instances Garrand and others (1982) reported iron-stained sandstone with radioactive fracture fill. Middleton (1980) did not describe basal arkose-conglomerate facies in either the Sunlight Basin or Clarks Fork Canyon areas, although the basal conglomerate of the Flathead Sandstone crops out at Beartooth Butte, several townships to the northwest, in sec. 30 of T. 58 N., R. 105 W.

The first site includes samples MFO-076 and MFO-077 from Garrand and others (1982) and corresponds to the Dilworth Bench location of Sutherland and Cola (2016), in sec. 8, T. 56 N., R. 104 W. No exact location is given by Garrand and others (1982), but the outcrop appears to be near the upstream end of Barrs Creek on top of Upper Dilworth Bench, more than 900 m above the Clarks Fork of the Yellowstone River. Garrand and others (1982) did not describe this outcrop of Flathead Sandstone, but they reported that sample MFO-076 contained 1,000 ppm lanthanum, 3,000 ppm titanium, 40 ppm yttrium, 200 ppm zirconium, and 4 ppm chemical U_3O_8. Both King (1991) and Sutherland and Cola (2016) noted that 1,000 ppm lanthanum might be a typographical error, as the sample contains only 40 ppm yttrium.

The second site in this area is a radioactive zone at the Precambrian-Cambrian contact on the north side of Clarks Fork Canyon, at its eastern end near Bald Peak, in SW1/4 sec. 16, T. 57 N., R. 103 W. Garrand and others (1982) described a medium-grained, light-orange to light-pink altered sandstone with iron-oxide staining in the basal Flathead. They also mentioned a sandstone 12 m above the Precambrian contact at this site; it is unclear if this is the same radioactive horizon or a different sandstone. Their sample MFO-540 appears to be of soil from a gully below the Precambrian outcrop, not the Flathead Sandstone. No other published information is known for this particular radioactive Flathead occurrence.

The third location is in the northeastern part of Sunlight Basin, where Garrand and others (1982) described a radioactive outcrop near the confluence of Russel Creek and the Clarks Fork of the Yellowstone River, southeast of Antelope Mountain, in SW1/4 sec. 19, T. 56 N., R. 104 W. The rock was described as medium-grained, pebbly, orange-rust colored, iron-stained, brittle sandstone in the lowermost 12 m of the Flathead Sandstone. Radioactivity at the outcrop measured 4 to 18 times background levels. No uranium ore minerals were observed, and measurements of chemical U_3O_8 were only somewhat elevated, suggesting some of the radioactivity may be associated with thorium. Sample MFO-530 contained 140 ppm equivalent U_3O_8, 49 ppm chemical U_3O_8, 2,000 ppm titanium, 100 ppm zirconium, and no detectable lanthanum or yttrium. Sample MFO-531 contained 40 ppm equivalent U_3O_8, 36 ppm chemical U_3O_8, 4,000 ppm titanium, 300 ppm zirconium, 30 ppm lanthanum, and 10 ppm yttrium. Garrand and others (1982) hypothesized that the radioactive material had been deposited along closely spaced fractures in the rock. It is unclear if this location is a paleoplacer.

The fourth location is at the nearby "Dead Indian Group" claims, 150 m east of Wyo. Highway 296 in sec. 8, T. 55 N., R. 104 W. At this site, Garrand and others (1982) described an iron-oxide-stained sandstone about 12–30 m above the contact with Precambrian granite. They reported radioactivity measurements of 2–10 times background levels, and they noted that the radioactivity appeared to be constrained by fractures and alteration along a minor fault. Sample MFO-532 at this location contained 0.02 percent chemical U_3O_8, 2,000 ppm titanium, 500 ppm zirconium, and 10 ppm yttrium. It is again unclear if this is a low-grade Flathead paleoplacer or if it represents a different mechanism of mineralization.

Lastly, Garrand and others (1982) mentioned an anomalous basal Flathead outcrop in SW1/4 sec. 6, T. 55 N., R. 104 W., near Sunlight Creek Bridge. They measured radioactivity of 3–4 times background at a brown to dark-brown outcrop. They hypothesized that ore distribution might be controlled by jointing perpendicular to bedding, They collected no samples and provided no further information.

Overall, because thorium was never measured at these locations, and because REE analyses are incomplete and mineralogical analyses are nonexistent, it is difficult to ascertain whether these zones of radioactivity in the Sunlight Basin area are related to paleoplacers in the Flathead Sandstone or some other form of mineralization. None of the Sunlight Basin area locations were visited for this study.

Southern Bear Lodge Mountains, center E1/2E1/2 sec. 33, T. 52 N., R. 63 W., Crook County

Gersic and others (1990) reported that a xenolith of Flathead conglomerate in the alkaline igneous complex of the southern Bear Lodge Mountain exhibited elevated REE concentrations. The sample (#55) contained 108 ppm thorium, 3 ppm uranium, 174 ppm lanthanum, 334 ppm cerium, 20 ppm yttrium, 1.01 percent titanium, and 590 ppm zirconium. These geochemical results suggest that the sample may be a paleoplacer. If true, this occurrence, although only an isolated xenolith, is the farthest east REE-bearing Cambrian-age paleoplacer known in Wyoming. Farther east, the Cambrian Deadwood Conglomerate of the Black Hills of South Dakota is known to contain gold. The Southern Bear Lodge Mountains location was not visited for this study.

PALEOPROTEROZOIC DEPOSITS

Geologic Background

The Precambrian metasedimentary rocks of southeastern Wyoming also host paleoplacer deposits. Like those in the Cambrian Flathead Sandstone, these radioactive conglomerates occur at the base of sedimentary sequences, immediately overlying major unconformities. The bulk of the deposits occur in two different metasedimentary units: the Magnolia Formation of the Deep Lake Group in the Medicine Bow Mountains and the Jack Creek Quartzite of the Phantom Lake Suite in the Sierra Madre. Although the age difference between these two formations is not trivial, in this report we discuss them together not only because previous work did so but also because of their geochemical and mineralogical similarities.

The Paleoproterozoic Phantom Lake Suite is stratigraphically the lowermost of three metasedimentary sequences preserved north of the Cheyenne Belt in the Sierra Madre and Medicine Bow Mountains. The suite consists of highly deformed, amphibolite-grade metasedimentary and metavolcanic rocks. Throughout the region, these rocks rest unconformably on Archean basement composed of gneiss, granite, and remnant greenstone belts. In places the Phantom Lake Suite is intruded by granite that is Neoarchean in age.

The Paleoproterozoic Deep Lake Group, the lowermost unit in the Snowy Pass Supergroup, is separated from the older Phantom Lake Suite by a major unconformity. The metasedimentary rocks of the Deep Lake Group are often less deformed than those of the Phantom Lake Suite. The metamorphic rank of the Deep Lake Group ranges from green schist to amphibolite. The lowermost units in the Phantom Lake Group are fluvial in origin, whereas deposition of the upper part of the group took place in marine and glaciomarine environments. The overlying Libby Creek Group also consists mostly of marine metasediments.

Additional information on the geologic history of Precambrian metasedimentary rocks in southeastern Wyoming can be found in Miller and others (1977), Karlstrom (1977), Karlstrom and Houston (1979b), Karlstrom and others (1983), Houston and Karlstrom (1992), Houston (1993), and Mammone and others (2022).

Previous Exploration

The first published description of radioactive conglomerates in southeastern Wyoming was by Miller and others (1977), who sampled and analyzed the basal Deep Lake Group near Arrastre Lake in the Medicine Bow Mountains. This open-file report was followed by a series of publications about uranium-bearing Precambrian conglomerates throughout southeastern Wyoming. These reports investigated new discoveries (Graff and Houston, 1977; Houston and others, 1977, 1979), outlined exploration strategies (Houston and Karlstrom, 1979), and added to knowledge of Precambrian stratigraphy in the area (Karlstrom and Houston, 1979a; Karlstrom and others, 1983; Houston, 1993), which culminated in reconnaissance drilling and geochemical analysis throughout the Medicine Bow Mountains and Sierra Madre (fig. 25; Karlstrom and others, 1981).

Most of the radioactive conglomerates in the Paleoproterozoic Phantom Lake Suite are in the northwestern Sierra Madre, in the Deep Gulch Conglomerate member of the Jack Creek Quartzite—specifically Unit 3 of Karlstrom and others (1981), a subarkosic, muscovite-rich quartz-pebble conglomerate. Houston and Karlstrom (1987) interpreted this unit as having been deposited in a braided-river system. Although uranium was the exploration target, Karlstrom and others (1981) found that much of the radioactivity in the Deep Gulch Conglomerate was related to the presence of thorium. It was later determined that the elevated thorium content was due to a relative abundance of monazite and possibly huttonite (Houston and Karlstrom, 1987). Compared to younger radioactive metaconglomerates in the Medicine Bow Mountains, the units near Deep Gulch in the Sierra Madre are generally thicker, coarser grained, and more continuous along strike (Houston and Karlstrom, 1987). Minor radioactive conglomerates occupying similar stratigraphic positions have also been described upsection of the Deep Gulch Conglomerate in the Jack Creek Quartzite as well as in the Rock Mountain Conglomerate in the Medicine Bow Mountains.

Significant deposits in the Paleoproterozoic Deep Lake Group occur at the base of the Magnolia Formation. Radioactive conglomerates at this stratigraphic position are most abundant in the northeastern Medicine Bow Mountains. Although these deposits are younger than those in the Phantom Lake Suite, they share many similarities. Unit 5 of Karlstrom and others (1981) in the basal conglomerate member of the Magnolia Formation is the most persistent radioactive conglomerate layer in the Medicine Bow Mountains. Houston and Karlstrom (1987) interpreted that the conglomerate had been deposited in an alluvial fan. In some places, the zone of interbedded quartzite and radioactive conglomerate is as much as 20 m thick, although enrichment within the zone is highly variable. Unlike the older Deep Gulch conglomerates in the Sierra Madre, the radioactivity of the conglomerates near the base of the Deep Lake Group is due mostly to uranium, not thorium. Houston and Karlstrom (1987) believed that the primary uranium- and thorium-bearing phases are probably uranothorite and coffinite. They suggested that uraninite, coffinite, and thorite may have been the original detrital minerals prior to metamorphism, but their conclusions were not definitive. Karlstrom and others (1981) also provided geochemical analyses for samples collected from a large number of surface transects and drillholes throughout the Medicine Bow Mountains and Sierra Madre. In this study, we focused on previously published results that showed elevated thorium concentrations, as they may be associated with enrichment in REE-bearing monazite or other heavy minerals.

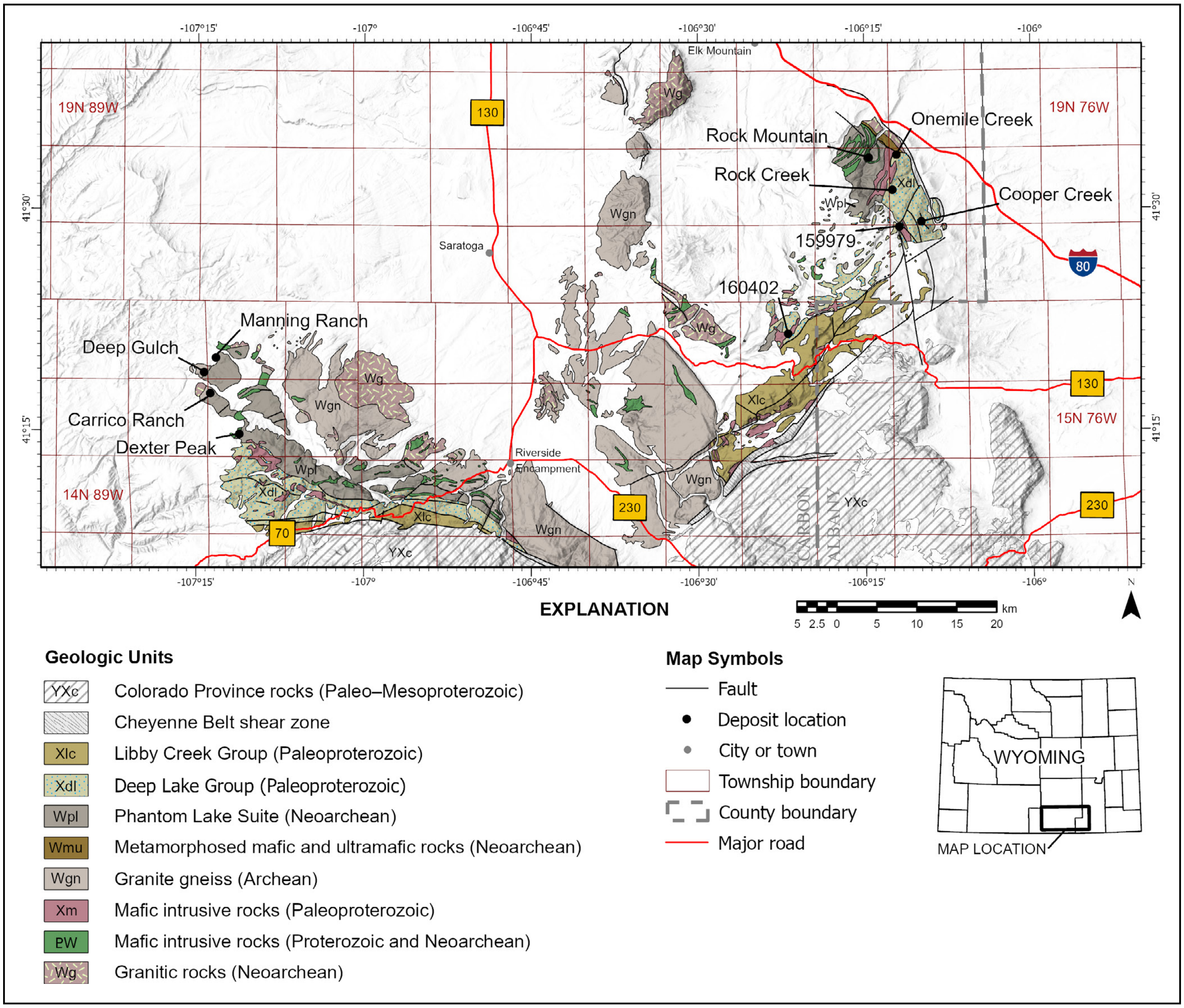

Figure 25. Locations of radioactive conglomerates in the Precambrian metasedimentary rocks of the Medicine Bow Mountains and Sierra Madre discussed in this report. Numerous drillholes and surface samples from Karlstrom and others (1981) are not shown. The sites depicted in the figure and visited for this study were those for which samples from Karlstrom and others (1981) were elevated in thorium content. Deposit-location labels 159979 and 160402 refer to samples collected from unnamed locations by Karlstrom and others (1981).

Geochemistry and Mineralogy

Thirteen Precambrian metaconglomerate and quartzite samples were analyzed geochemically for this study. Like the Flathead Sandstone samples, silver was measured at elevated, yet subeconomic, concentrations. Bismuth had a median concentration greater than five times crustal abundance, suggesting the possible presence of gold. Thorium and uranium concentrations were also often comparable to five times crustal abundance. Two samples from the Jack Creek Quartzite in the Sierra Madre contained significantly elevated HREEs (fig. 26). A number of samples from the Magnolia Formation in the Medicine Bow Mountains were moderately enriched in LREEs (fig. 27). Several Magnolia Formation samples also contained elevated tantalum and arsenic concentrations. Overall, total REEs in the Precambrian samples ranged from 20.3 ppm to 507 ppm, with an average of 221 ppm (a range of 24.3–605 ppm REO with an average of 263 ppm). Total LREEs averaged 158 ppm, with a range of 14.7 ppm to 454 ppm, and total HREEs averaged 58.9 ppm, with a range of 4.61 ppm to 334 ppm.

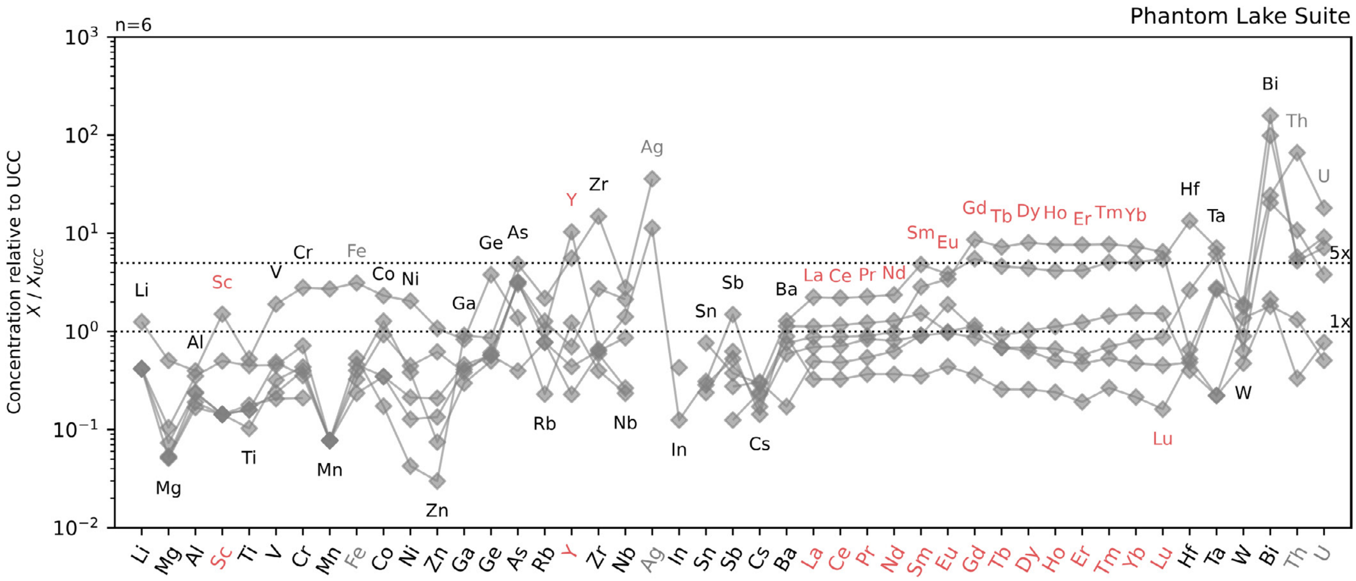

Figure 26. Concentrations relative to upper continental crust (UCC) of critical or economic elements for Paleoproterozoic Phantom Lake Suite samples measured in this study, mostly from the Jack Creek Quartzite in the Sierra Madre. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium, and n is the number of samples.

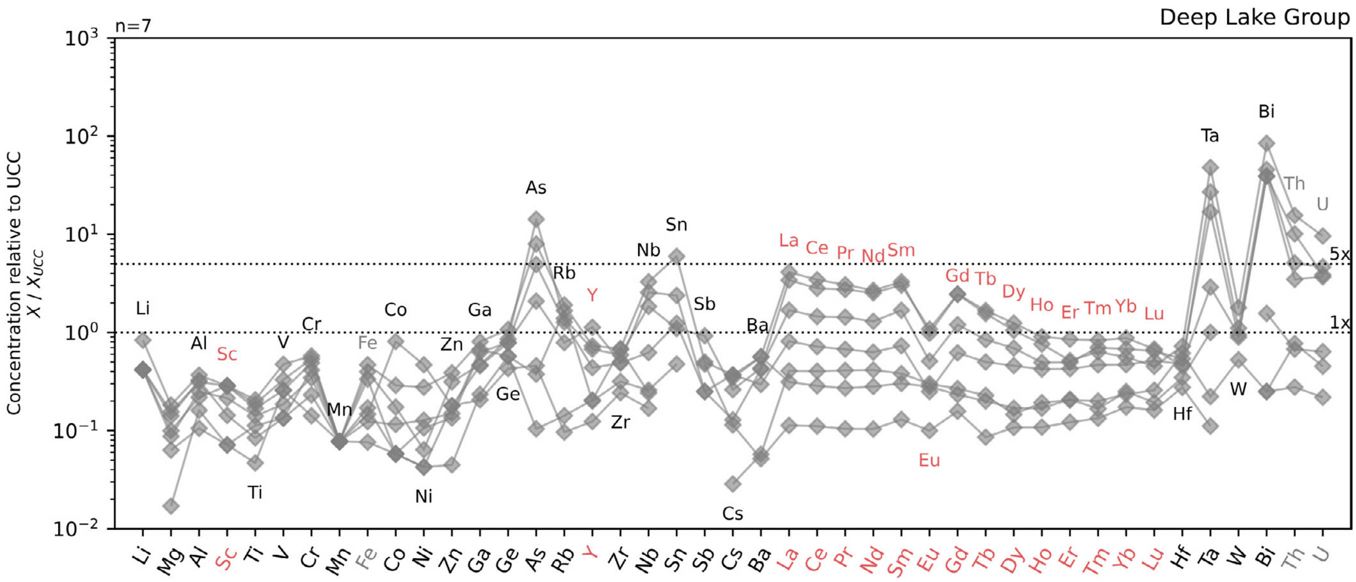

Figure 27. Concentrations relative to upper continental crust (UCC) of critical or economic elements for Paleoproterozoic Deep Lake Group samples measured in this study, primarily from the Magnolia Formation in the Medicine Bow Mountains. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium, and n is the number of samples.

Although our mineralogical analysis of these Precambrian occurrences was limited to just three samples, we did notice some trends, which may or may not represent the mineral systems as a whole. Unlike for the Cambrian Flathead Sandstone, mineralogical analysis did not reveal an abundance of detrital monazite in the Precambrian conglomerates. Rather, monazite was observed primarily as very fine inclusions in quartz and muscovite (fig. 28). Additional monazite appears to have precipitated along grain boundaries during diagenesis or metamorphism. A small amount of fine to very fine, rounded monazite, possibly detrital, was observed in the Magnolia Formation (fig. 28). Monazite is likely the primary host of LREEs. It is unknown what mineral is the primary host of HREEs in these rocks. A few small xenotime crystals were observed. Zircon grains, which are especially abundant in association with muscovite-rich bands in the Jack Creek Quartzite (sample HMS-DL-20220726-2A), also are often enriched in HREE. It is uncertain if the amount of zircon we observed is sufficient for the elevated HREE whole-rock concentrations measured (fig. 26).

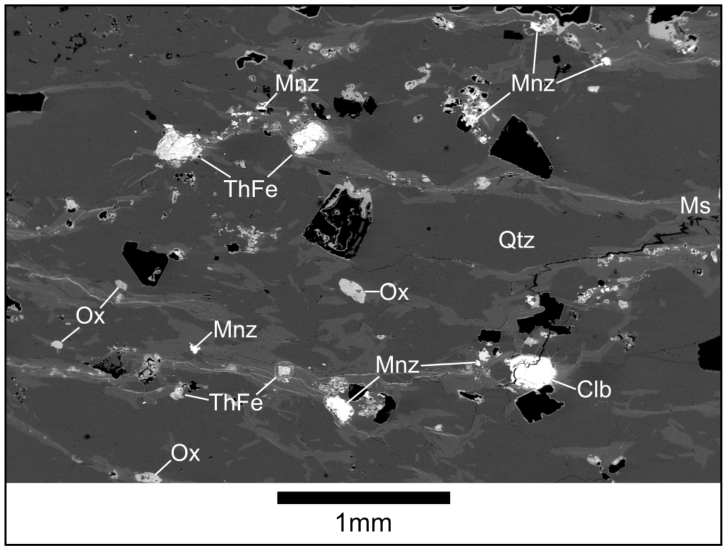

Figure 28. Annotated backscatter electron image of quartzite from the Magnolia Formation from the Medicine Bow Mountains. Heavy (bright) minerals include an unknown Th-Fe bearing phase or mixture (ThFe), monazite (Mnz), and Fe-oxide or hydroxide (Ox). Lighter minerals include quartz (Qtz) and muscovite (Ms). Th-Fe minerals coincide with micron-scale foliation-parallel Fe-oxide veins occupying the cleavage planes in muscovite. Sample is HMS-DL-20220818-1A from Onemile Creek.

The radioactivity of the Precambrian conglomerates in large part may be due to the presence of thorium-bearing phases other than monazite. Micron-scale uranium-thorium silicate minerals, possibly coffinite, were observed in the Jack Creek Quartzite (fig. 29). In both the Jack Creek Quartzite and the Magnolia Formation, we also observed an unidentified thorium-iron-oxide phase or mixture (figs. 28 and 30). This unidentified mineral is often fine grained and rounded in appearance. Houston and Karlstrom (1987) speculated that some of the thorium-bearing minerals in these rocks were originally detrital.

Bulk-mineral analysis with QEMSCAN was conducted for two samples from the Deep Gulch Conglomerate of the Phantom Lake Suite and one sample from the Magnolia Formation of the Deep Lake Group. Samples HMS-DL-20220726-01A and HMS-DL-20220726-02A from the Deep Gulch Conglomerate contained, respectively, 60.8 and 78.8 percent quartz, 13.6 and 8.4 percent feldspars, 19.6 and 8.7 percent muscovite, and 1.0 and 0.1 percent zircon. Both contained 0.2 percent other minerals, which may include monazite, epidote, garnets, and other unresolved mineral species. Sample HMS-DL-20220818-01A from the Magnolia Formation contained 64.4 percent quartz, 3.9 percent feldspar, 28.3 percent muscovite, 0.1 percent zircon, and 0.1 percent other minerals.

Previously published geochemical and mineralogical datasets are summarized in the descriptions for each deposit location.

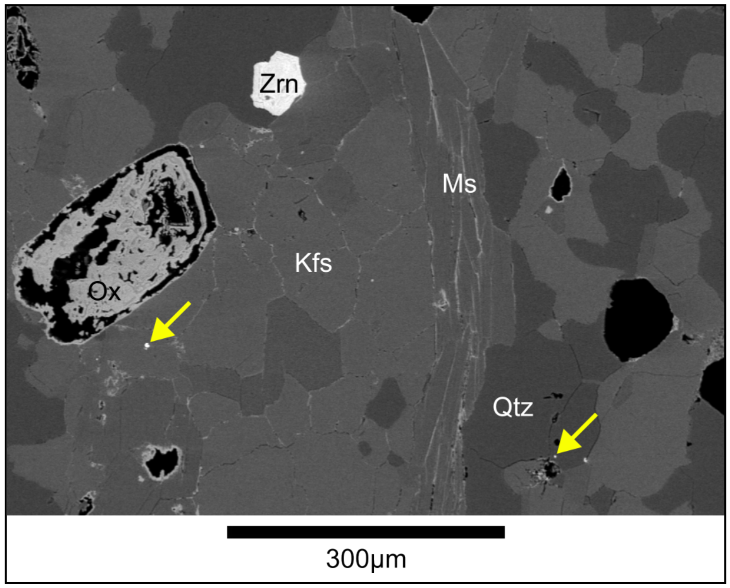

Figure 29. Annotated backscatter electron image of the Jack Creek Quartzite from the Sierra Madre. Yellow arrows point to micron-scale U-Th silicate minerals. Other minerals in the image include zircon (Zrn), Fe-oxides/hydroxides (Ox), K-feldspar (Kfs), muscovite (Ms), and quartz (Qtz). Sample is HMS-DL-20220726-1A from Carrico Ranch.

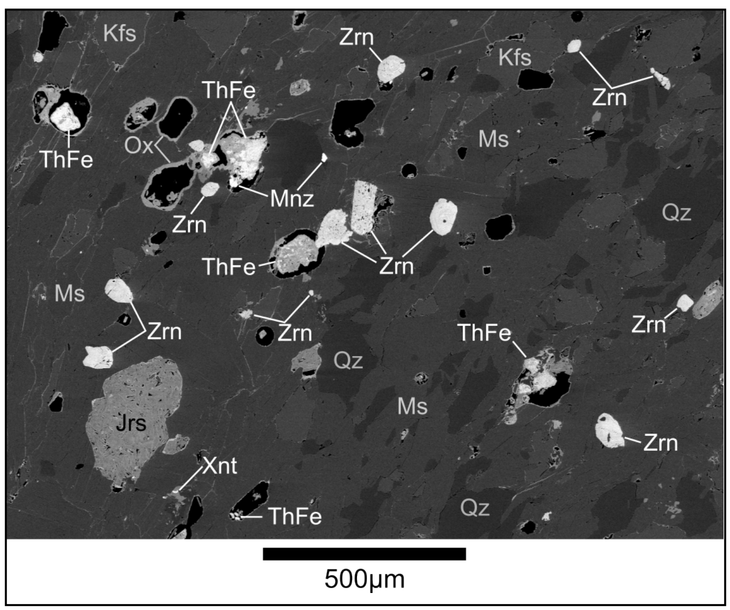

Figure 30. Annotated backscatter electron image of a mica-rich zone in the Jack Creek Quartzite from the Sierra Madre. Heavy (bright) minerals include zircon (Zrn), an unknown Th-Fe bearing phase or mixture (ThFe), monazite (Mnz), and xenotime (Xnt). The light-gray cluster to the lower left is jarosite (Jrs). Lighter minerals include muscovite (Ms), quartz (Qtz), and K-feldspar (Kfs). Th-Fe minerals coincide with micron-scale foliation-parallel Fe-oxide veins occupying the cleavage planes in muscovite. Sample is HMS-DL-20220726-2A from Carrico Ranch.

Site Descriptions, Phantom Lake Suite

Carrico Ranch, NW 1/4 sec. 7, T. 15 N., R. 87 W., Carbon County

The Carrico Ranch location is 55 km south of Rawlins on the northwestern flanks of the Sierra Madre. The Jack Creek Quartzite of the Phantom Lake Suite crops out along several ridges about 2.5 km east of Sage Creek Road (County Road 71). Karlstrom and others (1981) described a radioactive bed (Unit 3) in the Deep Gulch Conglomerate member of the Jack Creek Quartzite at this location.

The metasedimentary sequence exposed at Carrico Ranch consists primarily of quartzite, metaconglomerate, and chlorite-biotite-quartz schist. The beds are overturned and dip about 45 degrees to the northwest (fig. 31). Mafic intrusive rocks truncate the top of the sequence. The Deep Gulch Conglomerate at this location unconformably overlies biotite-quartz-plagioclase gneiss. Unit 3 of Karlstrom and others (1981) is composed of pink coarse-grained plane-bedded subarkose interbedded with 15- to 75-cm-thick radioactive quartz-pebble conglomerate beds, which are distinctly hematite-stained and contain pyrite. Radioactivity at the outcrop ranges from 3 to 12 times background levels.

Figure 31. Photograph of Jack Creek Quartzite at the Carrico Ranch location.

Along four surface transects (6–9) at "Ridge 2," Karlstrom and others (1981) collected samples that contained up to 245 ppm thorium. At "Ridge 1" to the southwest, they measured up to 524 ppm thorium (transects 1–5), and at "Ridge 3" to the northeast, they detected as much as 220 ppm thorium. Their highest-grade outcrop sample from the Carrico Ranch area (sample 152522) contained 87 ppm cerium, 24 ppm yttrium, and 409 ppm zirconium.

Karlstrom and others (1981) also collected data from six drillholes at Carrico Ranch (SM-1–SM-3), with the goal of assessing unleached uranium grade at depth. Their most highly radioactive drillhole sample (158460, from SM-2) contained 122 ppm yttrium, 185 ppm cerium, 222 ppm lanthanum, 1,841 ppm zirconium, and 2,596 ppm thorium.

For this study, two samples were collected from surface outcrop at "Ridge 2" of Karlstrom and others (1981), not far from drillholes SM-1 and SM-1A. The samples show elevated concentrations of arsenic, zirconium, REEs, hafnium, tantalum, bismuth, thorium, and uranium. Zirconium concentrations ranged from 527 ppm to 2,870 ppm. Thorium concentrations ranged from 112.5 to 695 ppm. Total REE concentrations were only 188–506 ppm, but HREEs, not LREEs, were significantly elevated relative to crustal abundance in sample HMS-20220726-2A. All detected elements associated with critical and economic minerals at the Carrico Ranch location are shown in fig. 32.

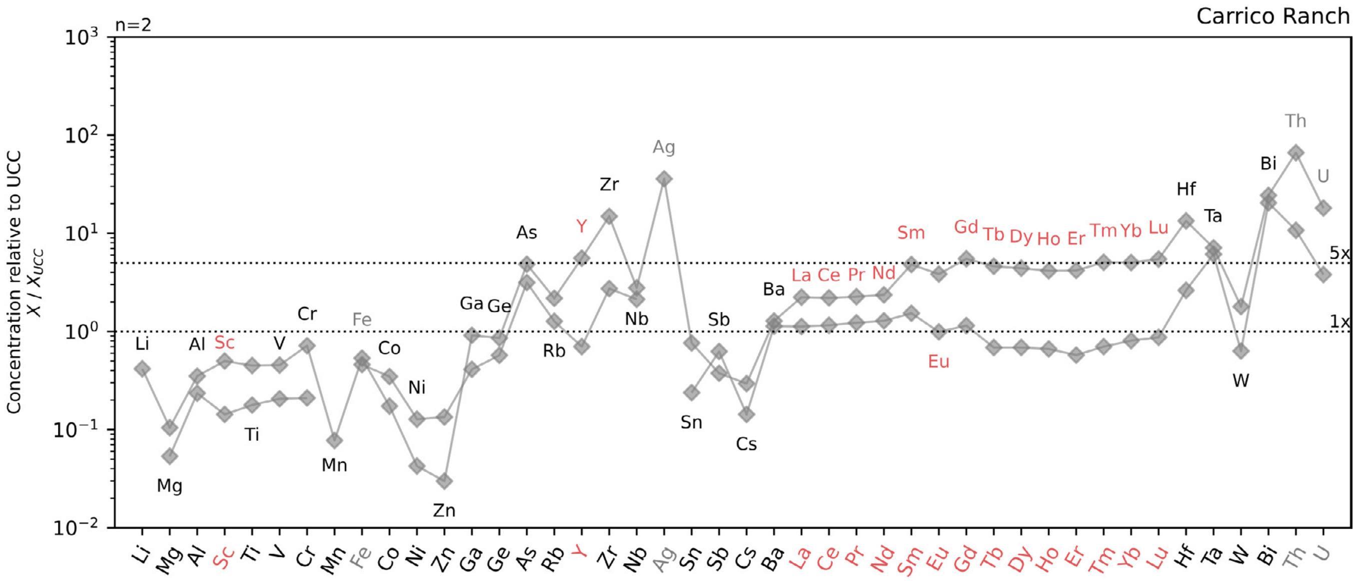

Figure 32. Concentrations relative to upper continental crust (UCC) of critical or economic elements for Jack Creek Quartzite samples collected at the Carrico Ranch location. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium, and n is the number of samples.

Deep Gulch, NE1/4 sec. 36, T. 16 N., R. 88 W., Carbon County

The Deep Gulch location is 53 km south of Rawlins along the northwestern flank of the Sierra Madre. The outcrop is 1.2 km east of Sage Creek Road. The deposit is in the overturned beds of the Deep Gulch Conglomerate member of the Jack Creek Quartzite (fig. 33). Strata generally dip 50 degrees to the northwest, but meso-scale drag folding is common. The base of the Deep Gulch Conglomerate here appears to rest unconformably on older gneiss intruded by mafic igneous rocks, but Karlstrom and others (1981) expressed uncertainty as to whether a number of para-conglomerate, schist, and quartzite units at the site belong to the Deep Gulch Conglomerate sequence or the older basement terrane. Upsection of and unconformably overlying these older metasedimentary units, the Deep Gulch Conglomerate consists of gray to pink, muscovitic, coarse-grained subarkose interbedded with conglomerates, one of which is 50 cm thick, radioactive, red-stained, and contains pyrite. The larger clasts in the radioactive conglomerate are stretched ellipsoid quartzite pebbles up to 6 cm in diameter (fig. 34). Radioactivity measurements at the outcrop are 2–7 times background levels.

Figure 33. Photograph of Jack Creek Quartzite at the Deep Gulch location.

Figure 34. Close-up photograph of the radioactive pebble conglomerate at the Deep Gulch location. Pen cap for scale.

Karlstrom and others (1981) reported geochemical analyses for samples collected from surface transects (13–17) and private drillholes (JP-1 and JP-2). The outcrop samples contained up to 205 ppm uranium and 839 ppm thorium, as well as 72 ppm cerium and 86 ppm yttrium. The highest-grade drillhole sample (158503) contained 490 ppm uranium, 483 ppm thorium, 107 ppm cerium, 107 ppm lanthanum, 72 ppm yttrium, and 2.51 ppm gold. Drillhole JP-3, located about 1 km northeast of Deep Gulch, did not encounter any radioactive conglomerate.

For this study, two outcrop samples were geochemically analyzed. Both samples contained bismuth, thorium, and uranium at concentrations greater than five times upper crustal abundance. Tantalum was also moderately elevated in both samples. One sample (HMS-DL-20220726-2A) showed elevated REE content. Although the total REE concentration in this sample was only 465 ppm, HREEs were all detected in concentrations greater than five times upper crustal abundance. All detected elements associated with critical and economic minerals at the Deep Gulch location are shown in fig. 35.

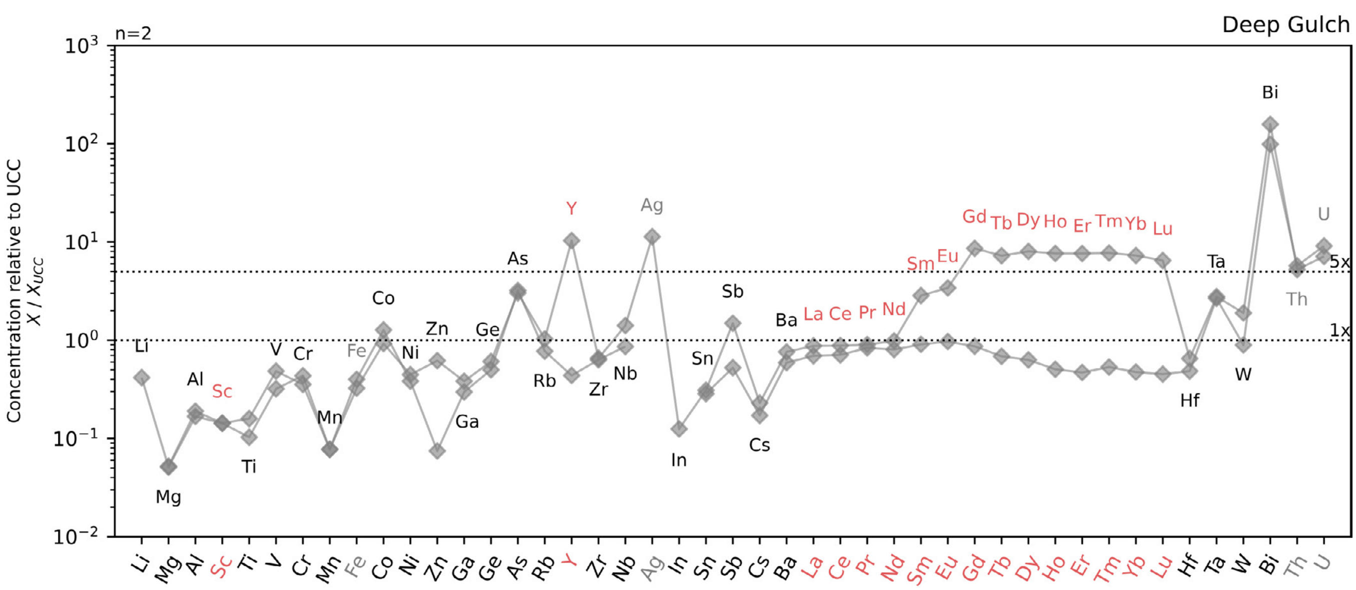

Figure 35. Concentrations relative to upper continental crust (UCC) of critical or economic elements for Jack Creek Quartzite samples collected at the Deep Gulch location. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium, and n is the number of samples.

Dexter Peak, N1/2 sec. 28, T. 15 N., R. 87 W., Carbon County

The Dexter Peak location is 60 km south of Rawlins along the western flank of the Sierra Madre, 1.5 km west of Deep Jack Road (USFS Road 830). The outcrop is on a ridgeline about 500 m southwest of Dexter Peak. Exposure consists of an overturned sequence of quartzite, schist, and phyllite. Conglomerate lenses here are similar to the Deep Gulch Conglomerate of the Jack Creek Quartzite at Carrico Ranch and Deep Gulch, but much of the metasedimentary sequence is not easily correlated.

Radioactive conglomerate was first reported at this location by Graff and Houston (1977), who collected samples that contained up to 131 ppm uranium and 10 ppm gold. Karlstrom and others (1981) appear to have collected samples along several surface transects, but we were unable to locate the corresponding data. In nearby drillholes (SM-4A and SM-4B), Karlstrom and others (1981) reported a maximum of only 7.1 ppm uranium, 66 ppm thorium, 58 ppm cerium, and 8 ppm yttrium.

We visited this location and observed a reddish quartz-pebble conglomerate that, although similar in appearance to those at Carrico Ranch and Deep Gulch, was not measurably radioactive (fig. 36). Karlstrom and others (1981) hypothesized that radioactive conglomerate is only found in discontinuous lenses in this area. Geochemical analysis of two samples collected during this study showed that one sample (HMS-DL-20220727-1A) was slightly enriched in vanadium, chromium, cobalt, nickel, HREEs, tungsten, bismuth, and thorium, whereas the other sample (HMS-DL-20220727-2A) was barren of critical minerals. All detected elements associated with critical and economic minerals at the Dexter Peak location are shown in fig. 37.

Figure 36. Photograph at the Dexter Peak location of red-stained conglomerate superficially similar to radioactive conglomerates observed elsewhere in the Sierra Madre. We were unable to locate any of the radioactive conglomerates reported by Graff and Houston (1977) or Karlstrom and others (1981) at this location.

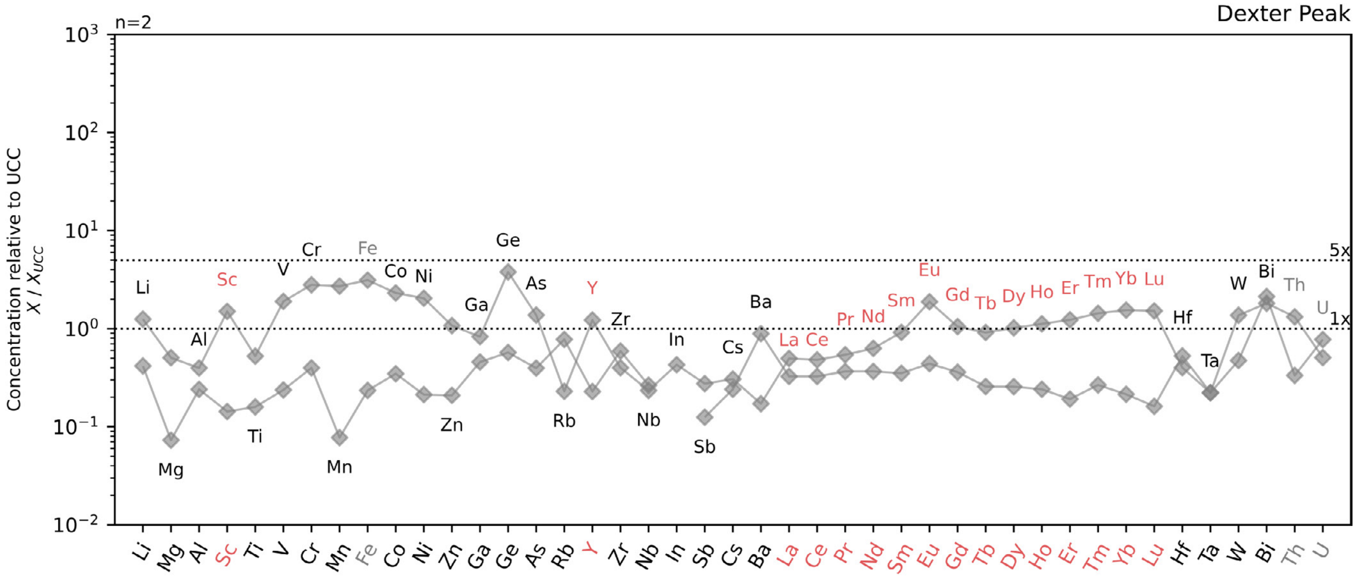

Figure 37. Concentrations relative to upper continental crust (UCC) of critical or economic elements for Jack Creek Quartzite samples collected at the Dexter Peak location. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium, and n is the number of samples.

Manning Ranch, NE1/4 sec. 30, T. 16 N., R. 87 W., Carbon County

The Manning Ranch location is on private land 50 km south of Rawlins, about 2.3 km northeast of Deep Gulch. Like other radioactive conglomerate occurrences in the Deep Gulch Conglomerate in this area, the metasedimentary sequence is exposed in the overturned limb of a large isoclinal fold, and beds dip uniformly about 40 degrees to the north-northwest. Karlstrom and others (1981) drilled at this location to determine uranium leaching, thickness of conglomerate units, and whether the conglomerate horizons seen in outcrops are continuous in the subsurface. They also collected samples along three surface transects (18–20), reporting geochemical results of up to 19.6 ppm uranium, 365 ppm thorium, 42 ppm cerium, and 10 ppm yttrium. In drillhole JP-4, they measured a maximum of 47.7 ppm uranium, 652 ppm thorium, 66 ppm cerium, 44 ppm lanthanum, and 47 ppm yttrium. The Manning Ranch location was not visited for this study.

Rock Mountain, S1/2 sec. 2, T. 18 N., R. 79 W., Carbon County

The Rock Mountain location is 2 km south-southwest of Arlington on the west flank of Rock Mountain. Unlike most radioactive conglomerates in the Medicine Bow Mountains, this occurrence appears to be in the Rock Mountain Conglomerate of the Phantom Lake Metamorphic Suite, which is correlative with parts of the Jack Creek Quartzite in the Sierra Madre. The structure of this area is complex, and the metasedimentary rocks that crop out here may be in the hinge of a reclined syncline (Karlstrom and others, 1981).

Karlstrom and others (1981) reported two radioactive zones in this area, and they collected and analyzed 18 non-transect outcrop samples. Most of their geochemical results were unremarkable, but one coarse-grained quartzite contained 396 ppm cerium, 30 ppm lanthanum, and 11 ppm yttrium. They also analyzed samples from two nearby drillholes (MB-10 and MB-15). In the subsurface, the radioactivity of the conglomerate horizons was less than of the surface outcrop, and geochemical analyses revealed only up to 9 ppm uranium and 15 ppm thorium. Karlstrom and others (1981) hypothesized that the radioactive zones in the Rock Mountain Conglomerate must be small and discontinuous. The Rock Mountain location was not visited for this study.

Site Descriptions, Magnolia Formation

Onemile Creek, E1/2 sec. 6, T. 18 N., R. 78 W., Carbon County

The Onemile Creek deposit is in the northern Medicine Bow Mountains, about 4 km south-southeast of Arlington and 3 km southwest of U.S. Interstate 80. The radioactive conglomerates are in the Paleoproterozoic Magnolia Formation of the Deep Lake Group, which here unconformably overlies the Phantom Lake Suite. Karlstrom and others (1981) described five subdivisions of the Magnolia Formation that consist mostly of subarkose, conglomerate, paraconglomerate, and schist. The principal radioactive zones correspond to several conglomerate beds in their Unit 5.

Some thin radioactive conglomerates were also reported in units 2 and 3. The metasedimentary sequence crops out on both limbs of an overturned syncline. Several faults and Neoarchean to Paleoproterozoic mafic intrusions truncate or interrupt the sequence in multiple locations. On the east limb of the syncline, three distinct, radioactive, micaceous, pyritic quartz-pebble conglomerates in Unit 5 crop out somewhat continuously for a distance of about 1 km. We recorded radioactivity levels of 4.5–9 times background at this outcrop (fig. 38).

Figure 38. Close-up photograph of radioactive conglomerate in the Paleoproterozoic Magnolia Formation at the Onemile Creek location. Scintillation meter, 13 cm by 8 cm, for scale.

Karlstrom and others (1981) reported geochemical analyses for samples collected from 10 surface transects (T1ABC through T8) and 11 drillholes (MB-16, EMB-1 through EMB-4, and EMB-6 through EMB-10) in the Onemile Creek area. Their most thorium-rich surface sample (157260 from transect T8) contained 915 ppm thorium, 3,952 ppm cerium, and 137 ppm yttrium. In the subsurface, their most thorium-rich sample (152103 in EMB-9) contained 1,143 ppm thorium, 824 ppm cerium, and 142 ppm yttrium. Among the few dozen zones of conglomerate in the Magnolia Formation at this locality, Karlstrom and others (1981) noted that several had uranium concentrations greater than 100 ppm.

For this study, four surface outcrop samples were geochemically analyzed. These samples were collected from Unit 5 of the Magnolia Formation along the ridgetop to the east of drillholes EMB-6, 7, and 8 from Karlstrom and others (1981). Three of four of the samples contained tantalum, bismuth, thorium, and uranium at concentrations greater than five times upper crustal abundance. The maximum measured thorium concentration was 163.5 ppm. Two samples had arsenic concentrations greater than five times upper crustal abundance. Niobium and LREEs were moderately elevated in three of the samples. Niobium concentrations ranged from 7.46 ppm to 39.3 ppm, with an average of 24.9 ppm, and total REE concentrations ranged from 116 ppm to 493 ppm, with an average of 317 ppm. All detected elements associated with critical and economic minerals in the Onemile Creek area are shown in fig. 39.

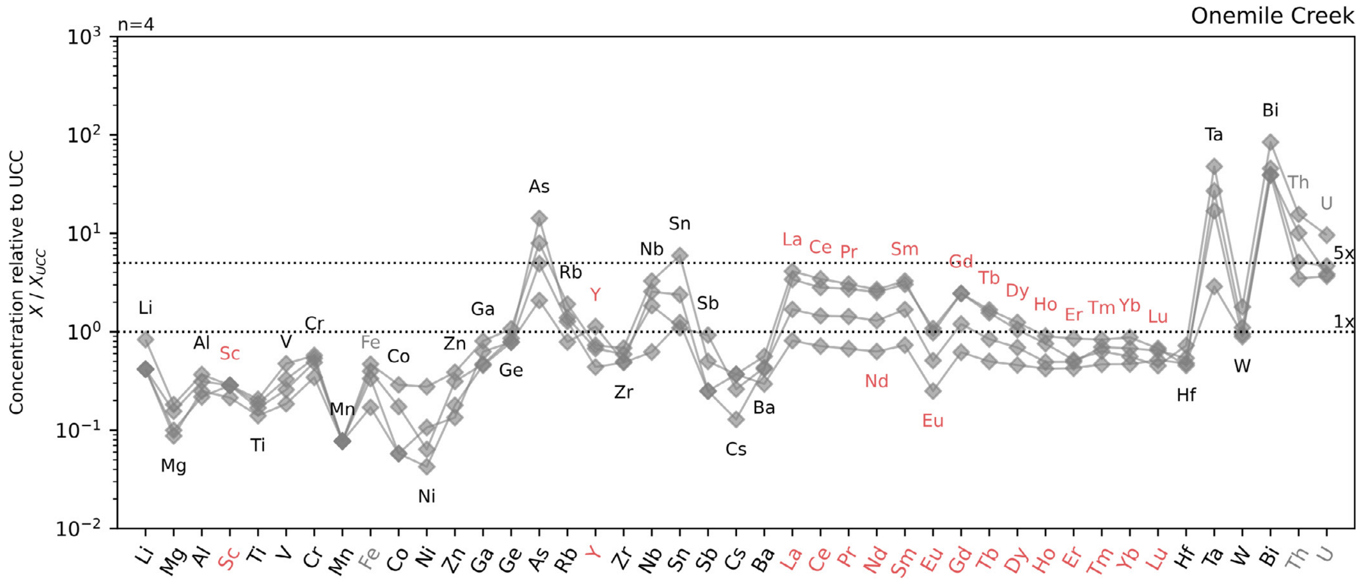

Figure 39. Concentrations relative to upper continental crust (UCC) of critical or economic elements for Magnolia Formation samples collected at the Onemile Creek location. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium, and n is the number of samples.

Cooper Creek, S1/2 sec. 33, T. 18 N., R. 78 W., Carbon County

The Cooper Creek location is in the northern Medicine Bow Mountains, 20 km north of the town of Centennial and 5 km northeast of Sand Lake Road (USFS Road 101). Karlstrom and others (1981) reported that outcrops of the Magnolia Formation in this area measured as great as six times background levels of radiation. Their nearby non-transect surface samples contained up to 485 ppm thorium and 150 ppm yttrium. Drillhole MB-4 did not encounter any noteworthy enrichment in critical minerals. The Cooper Creek location was not visited for this study.

Rock Creek (Threemile Creek), NW1/4 sec. 19, T. 18 N., R. 78 W., Carbon County

The Rock Creek location is 8 km south of Arlington in the northern Medicine Bow Mountains, where several radioactive conglomerates crop out within the Magnolia Formation. Outside of the Onemile Creek area, the Threemile Creek location features the greatest number of radioactive conglomerate occurrences in the Magnolia Formation.

Karlstrom and others (1981) reported geochemical analyses of surface and subsurface samples. Their non-transect outcrop samples contained up to 122 ppm uranium, 130 ppm thorium, and 70 ppm yttrium. Samples from drillholes EMB-5 and EMB-11 contained a maximum of 365 ppm uranium, 344 ppm thorium, 905 ppm lanthanum, 610 ppm cerium, and 45 ppm yttrium. Karlstrom and others (1981) noted that the basal contact of the Magnolia Formation appears to be gradational in this area, and they hypothesized that cobbles from older Colberg Metavolcanics were reworked into the basal Magnolia Formation during alluvial fan deposition. The Rock Creek location was not visited for this study.

Other Precambrian Sites

Two locations in the upper part of the Deep Lake Group were listed by Sutherland and Cola (2016) as potential REE deposits. We visited these sites and were unable to find any significant occurrences. Besides these, we did not visit any other potentially or marginally enriched sites in the Precambrian metasedimentary rocks of the Medicine Bow Mountains or Sierra Madre. Some of these apparently minor locations, which are numerous, are summarized in Karlstrom and others (1981), King (1991), and Sutherland and Cola (2016).

Unnamed (Sample 159979), NE1/4 sec. 6, T. 17 N., R. 78 W., Carbon County

Geochemical data for a sample collected at this location were reported by Karlstrom and others (1981). The sample (159979) was collected in the northeastern Medicine Bow Mountains near Sand Lake Road (USFS Road 101). The sample was from the Vagner Formation, which consists of quartzites and pebble conglomerates. King (1991) noted that, although this sample was reported to contain only 25 ppm uranium and 24 ppm thorium, it also contained 150 ppm yttrium. No other published data are known for this location.

For this study, we sampled conglomerate float from the base of a steep slope, but it was unclear if our location corresponded exactly to the location from Karlstrom and others (1981). Our geochemical results were unremarkable (HMS-DL-20220708-5A), and the sampling location was at most three times background levels of radiation.

Unnamed (Sample 160402), NE1/4 sec. 15, T. 16 N., R. 80 W., Carbon County

This occurrence was first reported by Karlstrom and others (1981). Sample 160402 was collected in the central Medicine Bow Mountains, north of Wyo. Highway 130. Because it only contained 2 ppm uranium, it was not of interest to Karlstrom and others (1981), but Sutherland and Cola (2016) noted that the sample contained 150 ppm yttrium. No other published data are known for this location.

For this study, we sampled a brown-orange-stained quartz-pebble conglomerate in the Lindsey Quartzite east of Upper Missouri Lake. Several 2- to 3-m-deep prospect pits were observed in the vicinity. Radioactivity levels were not measurably above background, and geochemical analysis of two samples (HMS-DL-20220810-2A, 3A) produced unremarkable results.

EOCENE FLUVIAL PLACERS

Geologic Background and Previous Exploration

Cenozoic stratigraphy in Wyoming consists largely of fluvial, lacustrine, and volcaniclastic deposition in intracontinental Laramide basins. The Eocene Wind River Formation in central and eastern Wyoming—as well as the roughly time-equivalent Wasatch and Willwood formations elsewhere in the state—is composed of mudstone, arkosic sandstone, and conglomerate deposited in flood plains and river channels. Sediments were sourced primarily from nearby active Laramide uplifts, where by this time crystalline basement had been exhumed. A several-million-year period of erosion and nondeposition followed deposition of the Wind River Formation. In some places, the boulder conglomerates of the Eocene Wagon Bed Formation were deposited on an erosional surface atop the Wind River Formation. In other locations, the Wind River Formation is directly overlain by the upper Eocene and lower Oligocene White River Formation, which contains a greater proportion of volcaniclastic material. Additional information on Eocene–Oligocene stratigraphy in Wyoming may be found in Roehler (1958), Larsen (1964), Denson and Harshman (1969), Harshman (1972), Emry (1973), Lillegraven and Ostresh (1988), Evanoff (1990), Lillegraven (1993), and references cited therein.

Zones of elevated radioactivity associated with thorium in monazite were first noted by Vine and Denson (1954) along the south edge of Bates Hole, at the northern rim of Shirley Basin. Additional nearby occurrences were noted by Love (1954) and Ellis (1977). The source of the radioactivity was first thought to be uranium, but these monazite-rich sandtsones are distinct from the roll-front-type uranium deposits in the Wind River Formation elsewhere in the Shirley Basin (Bailey, 1965; Harshman, 1972). King (1991) hypothesized that the Bates Hole deposits are fluvial placers in the Wind River and White River formations, and in a few instances possibly in Quaternary alluvium derived from these formations. Although King (1991) considered the Bates Hole area a significant potential source of REEs, Sutherland and Cola (2016) collected only one sample in the region due to poor exposure, finding no enrichment in REEs.

Most of the Eocene REE-bearing placers examined in this study are from the Shirley Basin (fig. 40), near the top of the Wind River Formation—although exact stratigraphic locations are uncertain. It is possible that a number of these placers are in the Wagon Bed Formation, where present, or a conglomerate near the base of the White River Formation. Elsewhere in the state, gold-bearing placers (Antweiler and others, 1980) and thorium-rich radioactive conglomerates (Sutherland and Cola, 2016) also have been reported in the Wind River Formation.

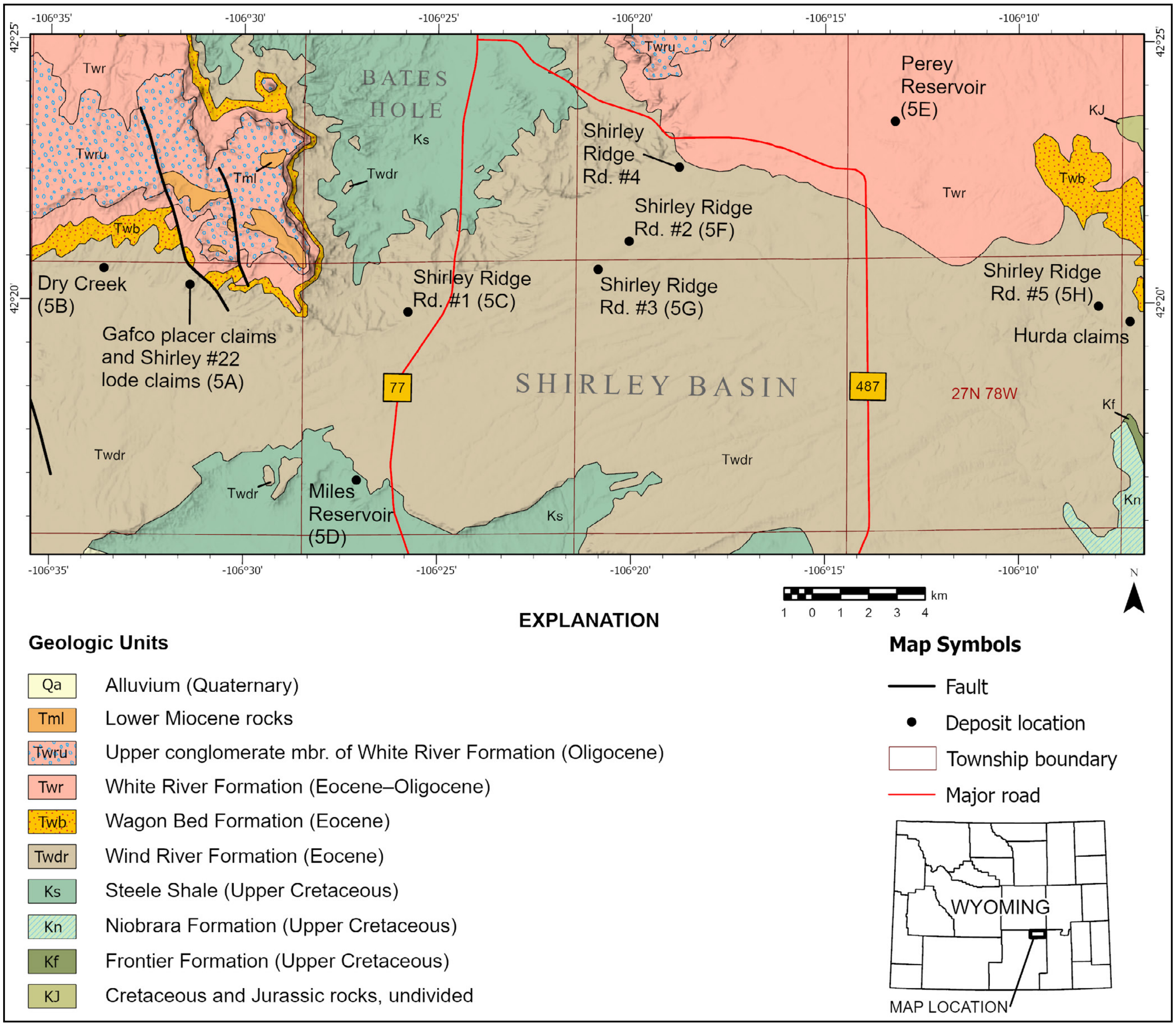

Figure 40. Reported locations of radioactive gravel residuum, mostly in the upper part of the Eocene Wind River Formation, in the Bates Hole-Shirley Basin area.

Geochemistry and Mineralogy

Ten samples from potential fluvial paleoplacers in the Eocene Wind River Formation were analyzed geochemically for this study (fig. 41). In addition to elevated-but-subeconomic silver concentrations, many of the samples were moderately enriched in LREEs and thorium. Total REE concentrations averaged 954 ppm, with a range of 164 ppm to 2,190 ppm. This is equivalent to total average REO of 1,120 ppm, with a range of 193 ppm to 2,560 ppm. Most of the REE content consists of LREE; the HREE fraction (total HREEs divided by total REEs) is only 0.058. Uranium, zirconium, and hafnium were also slightly elevated. Uranium concentrations averaged 7.29 ppm, with a range of 2.92–14.1 ppm. Zirconium concentrations averaged 264 ppm, with a range of 159–577 ppm. Hafnium concentrations averaged 7.20 ppm, with a range of 3.73–15.8 ppm.

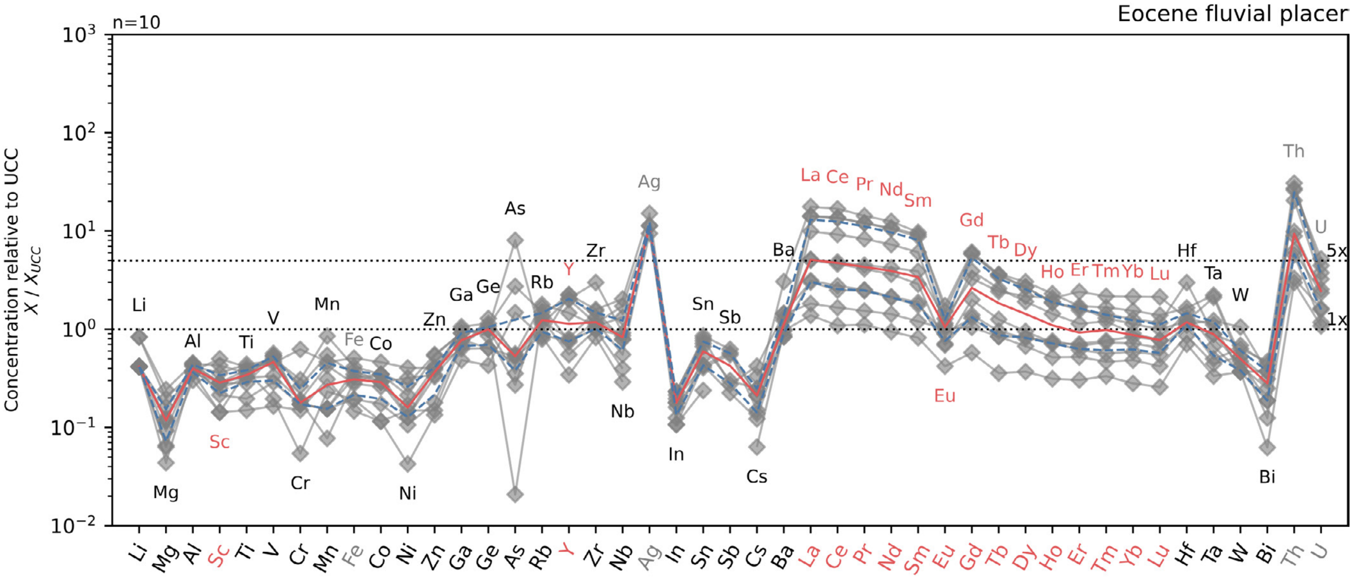

Figure 41. Concentrations relative to upper continental crust (UCC) of critical or economic elements for Wind River Formation samples measured in this study. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium. The solid red line is the median, and the dashed blue lines are the first and third quartiles, and n is the number of samples.

These geochemical results suggest that the deposits are paleoplacers enriched in monazite and zircon. This conclusion is supported by mineralogical analysis of grain mounts from a small number of samples. Fine-grained subangular to subrounded LREE-bearing detrital monazite is common (fig. 42). Other heavy minerals identified include zircon, barite, and ilmenite. The heavy minerals occur in sediment composed primarily of fine- to small-cobble-sized clasts of quartz, potassium feldspar, and various lithic fragments.

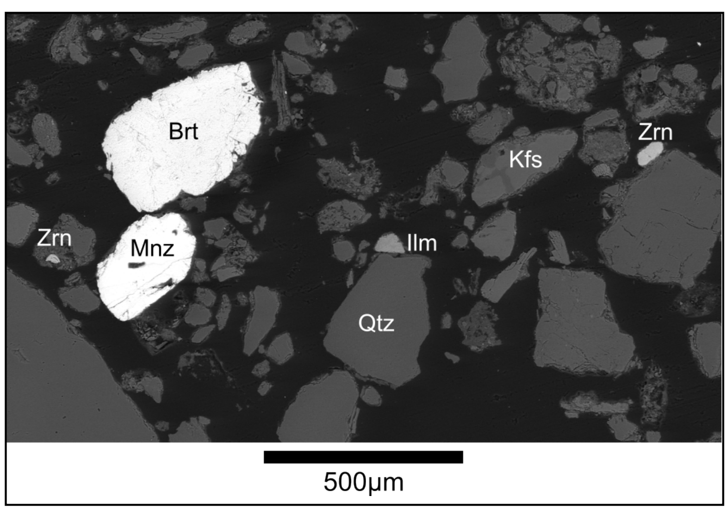

Figure 42. Annotated backscatter electron image of a grain mount from the Wind River Formation from the Shirley Basin. Heavy minerals (bright grains) are barite (Brt), monazite (Mnz), zircon (Zrn), and ilmenite (Ilm). The lighter minerals (dark-gray grains) include quartz (Qtz) and K-feldspar (Kfs). Sample is HMS-DL-20220706-1A from Bates Hole 5C.

Bulk-mineral analysis with QEMSCAN was performed on two samples (HMS-DL-20220628-02A and HMS-DL-20220830-02A), which were composed of 42.5–55.5 percent quartz, 36.6–50.0 percent feldspars, 0.4–0.8 percent titanium minerals, and 1.5–2.9 percent other minerals, which may include monazite, epidote, garnets, and other unresolved mineral species. Both samples contained less than 0.1 percent zircon.

Previously published geochemical and mineralogical datasets are summarized in the descriptions for each deposit location.

Site Descriptions

Bates Hole-Shirley Basin area

This study revisited six of the nine "Bates Hole area" locations summarized by King (1991). We successfully located and sampled radioactive conglomeratic residuum at five of the sites and one previously unpublished site. For many of these locations, the presence of REE-bearing monazite was unverified prior to this report. Based on elevated LREE concentrations and the identification of detrital monazite in a small number of grain mounts, these radioactive deposits appear to be fluvial paleoplacers. Site-specific descriptions are documented below.

Gafco placer claims and Shirley #22 lode claims (Bates Hole 5A), center sec. 3, T. 27 N., R. 81 W., Carbon County

The Gafco placer claims and Shirley #22 lode claims (Bates Hole 5A in King [1991]) are about 60 km south-southwest of Casper. The outcrops occur on a low ridge north of Dry Creek, near Meer Reservoir, about 3 km east of Dry Creek Road (County Road 103). The deposit is in the upper part of the Eocene Wind River Formation. It directly overlies variegated, poorly exposed floodplain mudstones and siltstones. Upsection and to the northeast, distinct gray-white tuffaceous sandstones of the White River Formation are exposed along the southwestern flank of Chalk Mountain.

The deposit itself consists of radioactive gravel residuum and sandy soil that armors a dissected pediment-like surface (fig. 43). Clasts are up to 10 cm in diameter, and consist of a wide variety of compositions (fig. 44), including igneous clasts. We observed radioactive residuum for a length of about 600 m in a narrow area trending east-northeast along the crest of a low ridge. Radioactivity measured 3–5 times background levels. Due to poor exposure the actual dimensions of the deposit are unknown.

Figure 43. Photograph of the ridge at the Gafco claims capped by radioactive gravel residuum derived from the Eocene Wind River Formation.

Figure 44. Close-up photograph of radioactive gravel residuum at the Gafco claims location. Scintillation meter, 13 cm by 8 cm, for scale.

Vine and Denson (1954) reported that heavy-mineral concentrates containing monazite were collected from coarse-grained arkosic sandstone and conglomerate near this location. A sample contained 1,200 ppm thorium and 30 ppm uranium. Whalen (1954) reported that a concentrate of a conglomerate, 1/50 of the original sample, contained 25 percent REEs, 6 percent ThO_2, and 0.25 percent U_3O_8. A sample of gravel residuum contained 9.7 percent heavy minerals, of which 23 percent were monazite, with trace zircon (Whalen, 1954). A spectrometer measurement by Griffin and others (1982) at this location yielded 830 ppm equivalent thorium and 29 ppm equivalent uranium, whereas geochemical analysis of this sample showed 470 ppm equivalent thorium and 23 ppm chemical U_3O_8 (MFB-256).

For this study, three gravel residuum samples were collected and geochemically analyzed. Thorium concentrations ranged from 215 ppm to 285 ppm, with a mean of 258 ppm. Total REE concentrations ranged from 1,240 ppm to 1,820 ppm, with an average of 1,620 ppm. Most of the REE content consisted of LREE; the HREE fraction of total REEs is only 0.051. All detected elements associated with critical and economic minerals in the Gafco claims area are shown in fig. 45.

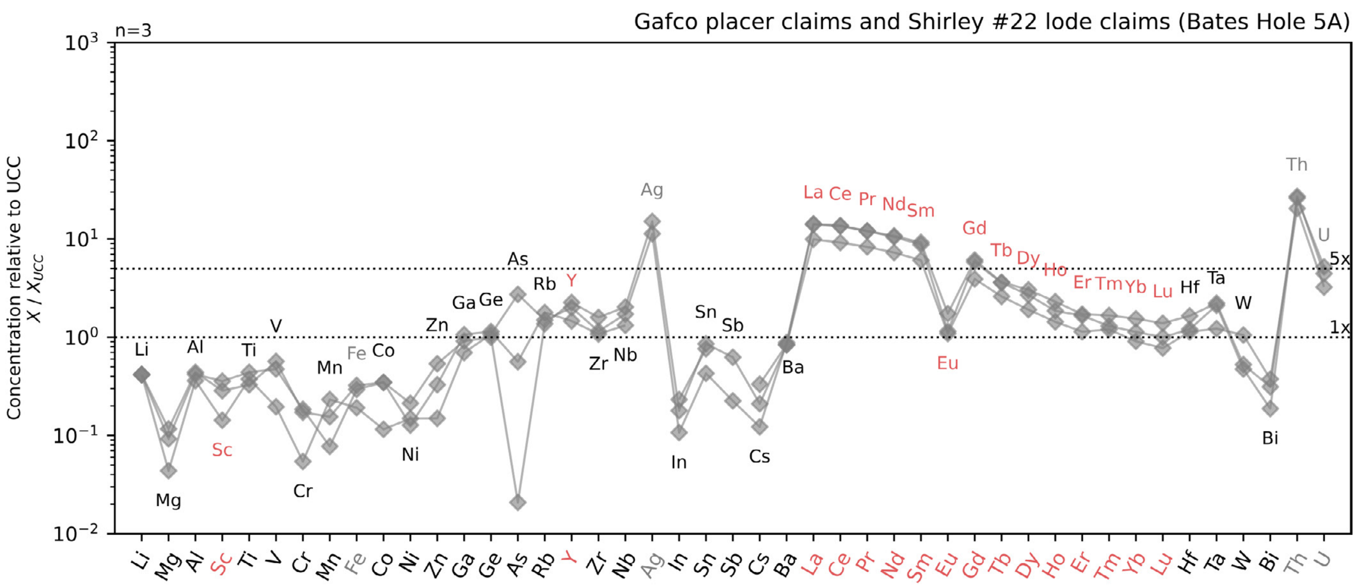

Figure 45. Concentrations relative to upper continental crust (UCC) of critical or economic elements for Wind River Formation samples collected at the Gafco placer and Shirley #22 lode claims (Bates Hole 5A). Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium, and n is the number of samples.

Dry Creek (Bates Hole 5B), NE1/4 sec. 5, T. 27 N., R. 81 W., Carbon County

This location is less than 3 km west of the Gafco placer claims (Bates Hole 5A), just northeast of where Dry Creek Road (County Road 103) crosses the Dry Creek drainage. Like at the Gafco claims, this deposit consists of heavily weathered gravel residuum and sandy soil, exposed about halfway up the side of a low ridge. Radioactivity of about two times background levels was sporadically observed along about 200 m of the hillside. Due to poor exposure, the actual dimensions of the deposit are unknown.

Griffin and others (1982) collected two gravel samples at this location. MFB-042 contained 700 ppm lanthanum, 70 ppm yttrium, 2,000 ppm titanium, 500 ppm zirconium, and 16.5 ppm chemical U_3O_8. MFB-043 contained 1,000 ppm lanthanum, 200 ppm yttrium, 5,000 ppm titanium, 500 ppm zirconium, and 55.5 ppm chemical U_3O_8. Based on these geochemical results, King (1991) suggested that this deposit, like the nearby Gafco claims, is a fluvial paleoplacer. No measurements were made for thorium. Griffin and others (1982) also collected a sandstone in this area (MFB-037), about 900 m south-southwest of the gravel samples, likely from a sandstone bed farther downsection in the Wind River Formation. The sample contained 150 ppm lanthanum, 1,500 ppm titanium, 20 ppm yttrium, and 300 ppm zirconium.

For this study, one sample from Dry Creek (Bates Hole 5B) was collected and analyzed geochemically. This sample (HMS-DL-20220628-4A) contained 390 ppm total REEs, 1,798 ppm titanium, 193 ppm zirconium, and 65.9 ppm thorium. All detected elements associated with critical and economic minerals at the Dry Creek (Bates Hole 5B) location are shown in fig. 46.

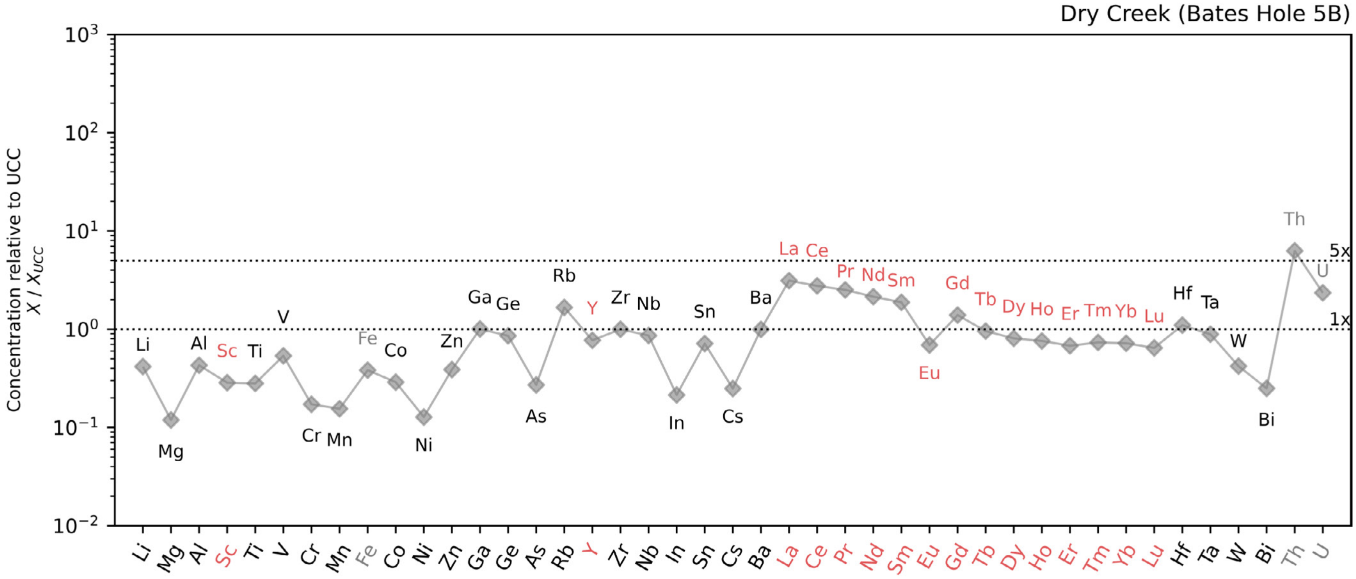

Figure 46. Concentrations relative to upper continental crust (UCC) of critical or economic elements for sample HMS-DL-20220628-04A of Wind River Formation collected at the Dry Creek (Bates Hole 5B) location. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium.

Shirley Ridge Road #1 (Bates Hole 5C), NW1/4 sec. 9, T. 27 N., R. 80 W., Carbon County

This deposit is about 1 km west of Wyo. Highway 77, on the north side of U.S. Bureau of Land Management Road 3129 along Shirley Rim. At this location, Love (1954) described a radioactive arkosic sandstone in either the upper Wind River Formation or lower White River Formation. The zone of radioactivity was about 30 m in diameter, but Love (1954) observed no uranium minerals. A grab sample contained 720 ppm equivalent uranium but only 60 ppm chemical uranium. Monazite was tentatively identified in the samples (Wilson, 1960).

We visited this location and observed radioactive gravel and sand residuum similar to that at the Gafco placer claims (Bates Hole 5A). There was also a conspicuous arkosic sandstone outcrop like that described by Love, but it was not radioactive. The radioactive gravel residuum extended for about 150 m along the crest of the rim (fig. 47). Radioactivity of up to nine times background levels was measured. Three samples of the gravel residuum were collected and analyzed, one of which (HMS-DL-20220706-1A) contained LREEs at greater than five times upper crustal abundance. Total REEs in these samples ranged from 164 ppm to 2,190 ppm, with an average of 904 ppm. Thorium concentrations ranged from 31.3 ppm to 322 ppm, with an average of 138 ppm. Zirconium and hafnium were also elevated in sample HMS-DL-20220706-1A, measuring 577 ppm and 15.8 ppm, respectively. All detected elements associated with critical and economic minerals at Shirley Ridge Road #1 (Bates Hole 5C) are shown in fig. 48.

Figure 47. Photograph of the southern rim of Bates Hole. The radioactive gravel residuum of the Shirley Ridge Road #1 (Bates Hole 5C) location caps the grassy ridge of Wind River Formation in the midground. In the background, the bulk of Chalk Mountain is composed of the White River Formation.

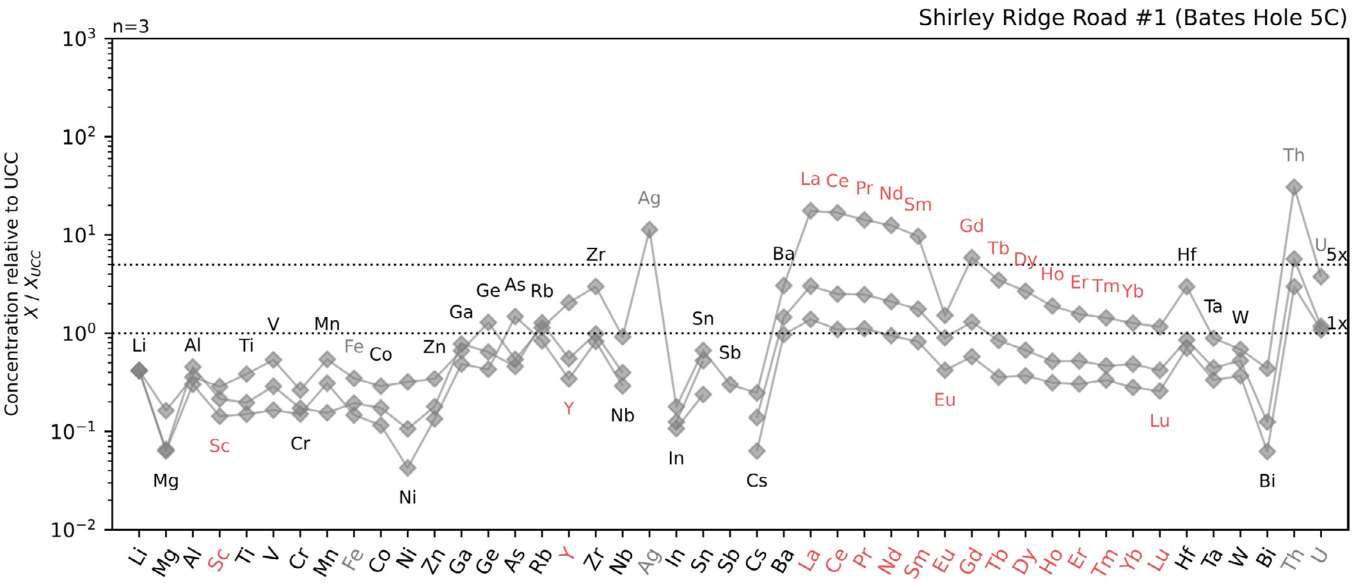

Figure 48. Concentrations relative to upper continental crust (UCC) of critical or economic elements for Wind River Formation samples collected at the Shirley Ridge Road #1 (Bates Hole 5C) location. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium, and n is the number of samples.

Miles Reservoir (Bates Hole 5D), sec. 29, T. 27 N., R. 80 W., Carbon County

Love (1954) described a second radioactive outcrop about 6.5 km south of Shirley Ridge Road #1 (Bates Hole 5C), in sec. 29, the east line of which coincides with Wyo. Highway 77. Like at the previous location, Love (1954) reported a zone of radioactivity, about 55 m in length, in an arkosic sandstone in either the upper Wind River Formation or basal White River Formation. Love (1954) noted that the sandstone at Bates Hole 5D may be slightly upsection of the one at Bate Holes 5C, but the lithologies are similar. The radioactive outcrop reportedly is on the north rim of a prominent ridge that runs roughly perpendicular to the north-south-oriented two-track roads in this section. Love (1954) observed no uranium minerals here. Three samples were collected along the outcrop, their composition ranging from 240 ppm to 630 ppm equivalent uranium but only 20 ppm to 50 ppm chemical uranium. Monazite was tentatively identified in samples from this location (Wilson, 1960).

We visited this area and were unable to locate either the arkosic sandstone described by Love (1954) or any other radioactive zone.

Perey Reservoir (Bates Hole 5E), roughly common corner secs. 17, 18, 19, and 20, T. 28 N., R. 78 W., Carbon County

This location is in the northern Shirley Basin, about 2.5 km northeast of where Wyo. Highway 487 intersects Shirley Basin North Road (County Road 6). At this site, Ellis (1977) collected six residuum samples (AAE-342–347) from the White River Formation. The samples contained between 50 and 100 ppm chemical thorium and less than 10 ppm equivalent uranium and chemical uranium. No analyses for REEs were conducted. Based on thorium content, King (1991) suggested this might be another monazite-bearing fluvial paleoplacer.

We did not visit this location. Its stratigraphic position in the White River Formation differs from other potential placers described in this section of this report. This site is also about 1 km northwest of known and developed Shirley Basin uranium roll-front deposits. The relationship, if any, between this potential fluvial paleoplacer and the uranium roll-front deposits is unclear.

Shirley Ridge Road #2 (Bates Hole 5F), SW1/4 sec. 32, T. 28 N., R. 79 W., Carbon County

This possible paleoplacer is about 2.2 km southwest of Shirley Ridge Road (County Road 2), about 5.9 km northeast of its intersection with Wyo. Highway 77. Ellis (1977) collected six residuum samples from the Wind River Formation (AAE-320–325), which contained 200–1,900 ppm equivalent thorium, 148–1,611 ppm chemical thorium, 4–40 ppm equivalent uranium, and 5–24 ppm chemical uranium. The sample with the greatest thorium content was at the surface. Likely because of the high thorium concentrations, King (1991) suggested this might be another heavy-mineral-bearing fluvial paleoplacer.

We visited the location for this study and were unable to find the radioactive residuum sampled by Ellis (1977) or any other radioactive zone.

Shirley Ridge Road #3 (Bates Hole 5G), center west line of NE1/4 sec. 6, T. 27 N., R. 79 W., Carbon County

This location is 2 km southwest of Shirley Ridge Road (County Road 2), about 4.2 km northeast of its intersection with Wyo. Highway 77 and 1 km southwest of Shirley Ridge Road #2 (Bates Hole 5F). Ellis (1977) collected one sample of residuum from the Wind River Formation (AAE-319). The sample contained 120 ppm equivalent thorium and less than 10 ppm each chemical uranium and equivalent uranium.

We visited this location and observed a radioactive zone about 500 m long along the south bank of an unnamed small reservoir and intermittent drainage. Radioactivity at the outcrop measured 2–3 times background levels. The radioactive material consisted of poorly exposed gravel residuum and sandy soil (fig. 49), like that at other Bates Hole locations, in a relatively resistant bed in the upper Wind River Formation.

Figure 49. Close-up photograph of gravel residuum in the Wind River Formation at the Shirley Ridge Road #3 (Bates Hole 5G) location. Note hammer for scale.

For this study, one residuum sample was collected (HMS-DL-20220830-2A). It was moderately enriched in LREEs, and contained 233 ppm zirconium, 390 ppm total REEs, and 93 ppm thorium. All detected elements associated with critical and economic minerals at Shirley Ridge Road #3 (Bates Hole 5G) are shown in fig. 50.

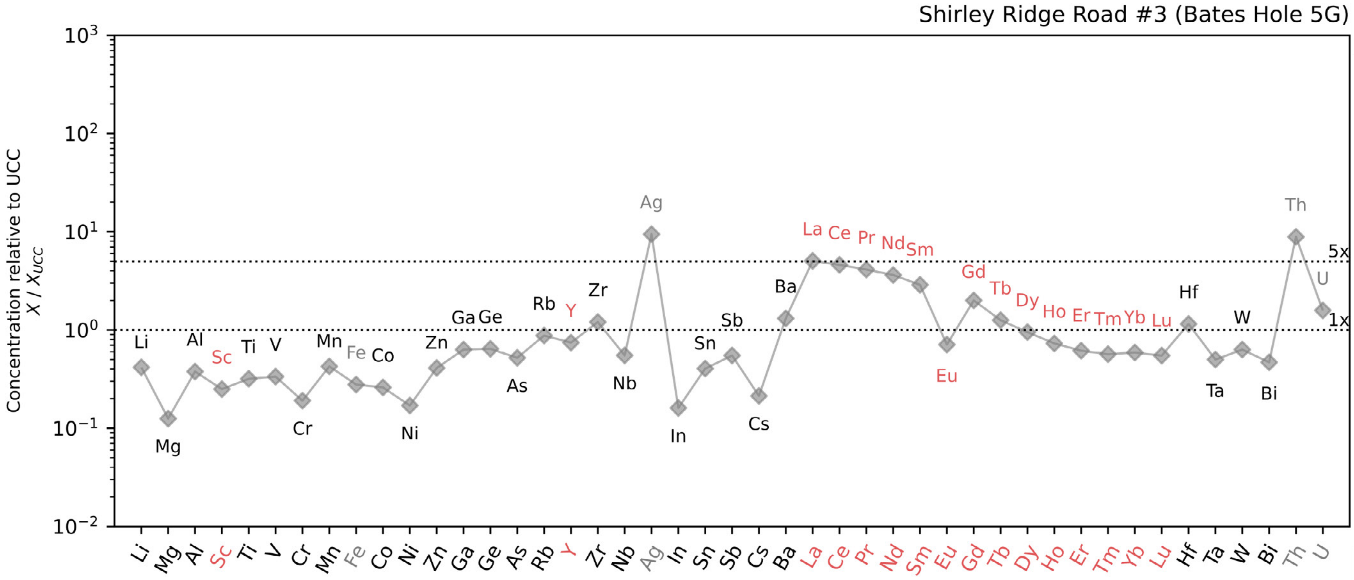

Figure 50. Concentrations relative to upper continental crust (UCC) of critical or economic elements for sample HMS-DL-20220830-2A of Wind River Formation collected at the Shirley Ridge Road #3 (Bates Hole 5G) location. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium.

Shirley Ridge Road #4, SW1/4 sec. 21, T. 28 N., R. 79 W., Carbon County

We collected an additional sample in the Bates Hole area sample at this location, about 1 km south-southwest of the intersection of Shirley Ridge Road (County Road 2) and Wyo. Highway 487. No previously published data are known to suggest the presence of a paleoplacer here. Slightly elevated radioactivity (at most 2 times background) was observed along a terrace-like surface for a distance of about 250 m. This surface was armored with gravel residuum similar to that observed at other paleoplacer deposits in the area. One sample was collected and analyzed (HMS-DL-20220830-1A). It was somewhat enriched in thorium (34.5 ppm) and contained zirconium and REEs at concentrations slightly greater than upper crustal abundance. All detected elements associated with critical and economic minerals at Shirley Ridge Road #4 are shown in fig. 51.

Shirley Ridge Road #5 (Bates Hole 5H), N1/2 sec. 12, T. 27 N., R. 78 W., Carbon County

This location is beside Shirley Ridge Road (County Road 2), about 8 km east of its intersection with Wyo. Highway 287. King (1991) suggested this is another low-grade paleoplacer. However, the original descriptions by Griffin and others (1982) of an altered yellow-orange fine-grained sandstone (MFB-234) and a carbonaceous shale (MFB-233) are inconsistent with other Eocene paleoplacers in the region, which typically are found within coarse sand-gravel residuum. In these samples, lanthanum, yttrium, and zirconium were only slightly elevated, and thorium was not measured. This location is also about 1 km east of known uranium roll-front deposits. There is currently no convincing evidence that this is a paleoplacer or a significant occurrence of critical minerals. Nonetheless, this remains an unverified deposit. The Shirley Ridge Road #5 (Bates Hole 5H) location was not visited for this study.

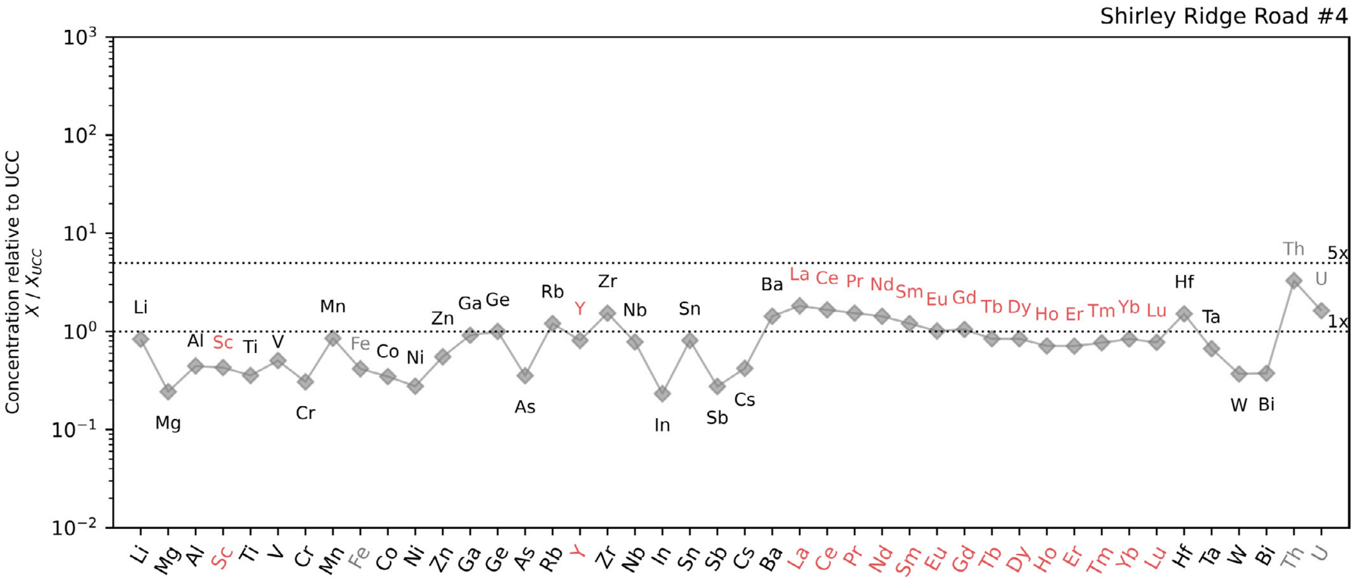

Figure 51. Concentrations relative to upper continental crust (UCC) of critical or economic elements for sample HMS-DL-20220830-1A of Wind River Formation collected at the Shirley Ridge Road #4 location. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium.

Hurda claims, center W1/2 sec. 7, T. 27 N., R. 77 W., Carbon County

Griffin and others (1982) analyzed a sample of altered pink silty arkosic sandstone in the White River Formation at this location, about 0.8 km east of Shirley Ridge Road (County Road 2), 1.3 km southeast of the Shirley Ridge Road #5 (Bates Hole 5H) location described above. Sample MFB-005 from Griffin and others (1982) contained 300 ppm lanthanum, 100 ppm yttrium, 50 ppm zirconium, and 52 ppm chemical U_3O_8. King (1991) suggested that the slightly elevated lanthanum and yttrium may indicate a fossil placer deposit. A nearby carbonaceous shale reportedly measured 10 times background radiation (Whalen, 1954). Like Shirley Ridge Road #5, this location does not match the description of other known paleoplacers in the region. Whether this location constitutes a paleoplacer is uncertain. The Hurda claims were not visited for this study.

Bonneville Reservoir (Northern Wind River Basin), SE1/4 NE1/4 sec. 19, T. 39 N., R. 93 W., Fremont County

Unlike the Bates Hole-Shirley Basin occurrences, this location is in the northern Wind River Basin, 13 km northeast of Shoshoni, 6.5 km east of U.S. Highway 20/Wyo. Highway 789, and 11.3 km south of where the highway enters the Wind River Canyon and the Owl Creek Mountains. The outcrop is at the base of a low ridge 3 km northeast of Bonneville Reservoir. The occurrence consists of a small zone of radioactive interbedded conglomerate and coarse, limonite-stained sandstone in the Eocene Wind River Formation (Thaden, 1978). Finer-grained sandstones comprise the bulk of the hill upsection to the east, and variegated mudstones are poorly exposed downsection of the deposit. Clasts in the conglomerate are of varying composition, up to about 15 cm in diameter, and subrounded to rounded. The radioactive zone is about 1.5 m thick and confined to an outcrop less than 6 m wide (fig. 52). Radioactivity at the outcrop measured 2–5 times background levels. Sutherland and Cola (2016) collected one sample (20150804LC-5) near this location, which contained total REEs of 691 ppm. Their analysis also yielded 102 ppm thorium and 236 ppm zirconium.

For this study, one sample was collected and geochemically analyzed (HMS-PW-20220803-1AB). It contained 720 ppm total REEs, 104 ppm thorium, and 256 ppm zirconium. All detected elements associated with critical and economic minerals at Bonneville Reservoir location are shown in fig. 53.

Figure 52. Photograph of radioactive conglomerate in the Wind River Formation at the Bonneville Reservoir location in the northern Wind River Basin.

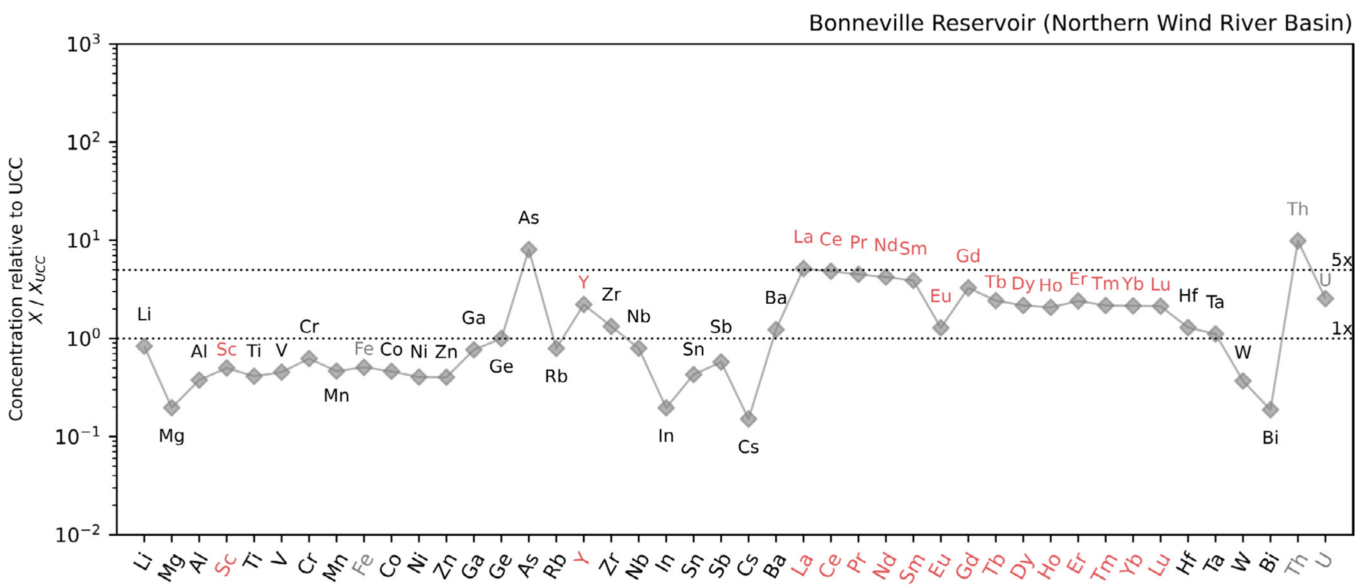

Figure 53. Concentrations relative to upper continental crust (UCC) of critical or economic elements for sample HMS-PW-20220803-01AB of Wind River Formation collected at the Bonneville Reservoir location in the northern Wind River Basin. Black-colored elements are associated with critical minerals. Gray elements are associated with economic, non-critical minerals. Red elements are REEs, including scandium and yttrium.

Southwest Pine Mountain, center S line NW1/4 sec. 31, T. 53 N., R. 84 W., Natrona County

This location is about 40 km west of Casper, 2 km west of Oil Camp Road (Strohecker Road; County Road 210), about 10 km southeast of the intersection of Oil Camp Road with U.S. Highway 20/26. The outcrop is on the western flank of the Pine Mountain anticline, at the eastern margin of the Wind River Basin. Here, the Eocene Wind River Formation unconformably overlies more steeply dipping Cretaceous formations.

During mapping of the Casper 30' x 60' quadrangle, Hunter and others (2005) collected a sample (WGS-0501) of yellowish-brown, medium- to coarse-grained sandstone with limonite staining. The sample contained 1,390 ppm total REEs, 57.7 percent Fe_2O_3, 12.95 percent TiO_2, 2,500 ppm vanadium, greater than 10,000 ppm zirconium, 248 ppm hafnium, 119 ppm thorium, and 26.2 ppm chemical uranium. Hunter and others (2005) also indicated that the rock contained monazite. Sutherland and Cola (2016) revisited the area and collected samples of petrified wood, silicified bones, and septarian concretions, but not of the sandstone sampled by Hunter and others (2005).

We visited the area for this study. Although we did find yellowish-brown, medium- to coarse-grained sandstone with limonite staining, none of the outcrops we examined were radioactive, and the mineralogy, as determined in hand sample, was not that of a fossil placer or any other type of critical mineral deposit. Nonetheless, the geochemical results from Hunter and others (2005) strongly suggest that a paleoplacer deposit exists in the area, but we were unable to locate it.

CONCLUSIONS

REE-bearing radioactive conglomerates occur in the Cambrian Flathead Sandstone throughout the state. Most of the REE content in the basal Flathead placers is hosted in fine-grained detrital monazite. Most previous work has been at Bald Mountain in the northern Bighorn Mountains, which is a relatively unique location in that the paleoplacer deposit is relatively well exposed, with little overburden. Elsewhere in Wyoming, radioactive conglomerate lenses at the base of the Flathead are very poorly exposed, and their dimensions are unknown.

Radioactive conglomerates also occur in deformed Precambrian metasedimentary rocks in the Medicine Bow Mountains and Sierra Madre. The Paleoproterozoic Magnolia Formation is enriched mostly in LREEs, thorium, and uranium, whereas the Deep Gulch Conglomerate member of the Jack Creek Quartzite contains elevated HREEs and thorium. Although very fine monazite was observed in these formations, the radioactivity of the conglomerates may in large part be due to the presence of other thorium-bearing minerals. For instance, an unidentified thorium-iron phase or mixture was observed in both the Magnolia Formation and the Jack Creek Quartzite. A uranium-thorium silicate mineral, possibly coffinite, was also observed in the Jack Creek Quartzite. These thorium minerals are generally of micron size and occur as inclusions or in association with cleavage planes.

Like the Flathead Sandstone, the Eocene Wind River Formation also contains conglomerates that are radioactive due to the presence of fine-grained detrital monazite. Most of these are in the Bates Hole-Shirley Basin area, but a small number are known or suspected elsewhere in Wyoming.

Although these different radioactive conglomerates occur in stratigraphic intervals that have vastly different geologic histories, there are a few similarities. First, the occurrences all appear to be placers deposited in gravel-bed rivers or streams, likely close to the source rock. Second, they were all deposited at times when Archean rocks of the Wyoming Craton were exposed and being actively weathered and eroded. To illustrate, the basal conglomerate of the Paleoproterozoic Magnolia Formation is radioactive where it rests unconformably on Neoarchean granites but not where it overlies deformed metasedimentary rocks of the Phantom Lake Suite (Karlstrom and others, 1981). In addition, some researchers have suggested that the primary source of uranium in younger formations in the region is granite rich in thorium and uranium in the Wyoming Craton (Stuckless and Nkomo, 1978; Houston, 1979). It is possible that Archean-age cratonic rocks were also sources for monazite placers in the Precambrian, Middle Cambrian, and late Eocene. Moreover, greenhouse conditions in the Middle Cambrian and late Eocene would have facilitated weathering of these source rocks, resulting in the in-place formation of regolith preferentially enriched in heavy minerals resistant to weathering (Sell, 2022).

Overall, radioactive basal conglomerates of Precambrian, Cambrian, and Eocene age in Wyoming are potential sources of critical minerals, particularly of REE-bearing monazite. Although most of these potential deposits are poorly exposed and of unknown size—likely small—the geochemical and mineralogical results from this study confirm enrichment in critical minerals where in some cases it was previously only suggested by elevated radioactivity or thorium content. The results of this study also demonstrate that critical-mineral-bearing fluvial paleoplacers are not necessarily limited to a single stratigraphic interval or geographic region in Wyoming.

ACKNOWLEDGMENTS

We would like to express our gratitude to the State of Wyoming for funding this project. The State's commitment to supporting innovative scientific endeavors has been instrumental for promoting the beneficial and responsible development and use of Wyoming's geologic, mineral, and energy resources.

We extend our sincere appreciation to the numerous landowners and claimholders who graciously granted us access to their properties. Without their collaboration and cooperation, our fieldwork would not have been possible.

We also wish to acknowledge the dedicated individuals who joined us in the field, contributing their time and expertise to the project. In particular, we are extremely grateful to David H. Malone of Illinois State University and his student Michael N. Sell, who generously shared samples they collected during bedrock mapping of the Bald Mountain 7.5' quadrangle.

Finally, we are grateful to our peers at the WSGS who meticulously examined our manuscript, offering invaluable suggestions and constructive criticisms. Their insightful feedback has greatly improved this report.

CREDIT AUTHOR STATEMENT

Derek T. Lichtner: Conceptualization, Methodology, Formal analysis, Investigation, Data Curation, Writing—Original Draft, Visualization, Supervision, Project Administration; Jon M. Krupnick: Methodology, Investigation, Data Curation, Writing—Original Draft; Christopher J. Doorn: Investigation, Writing—Review and Editing, Visualization; Patricia M. Webber: Conceptualization, Investigation

Others contributors: Erin A. Campbell: Writing—Review and Editing, Supervision, Funding acquisition; Ranie M. Lynds: Writing - Review and Editing, Supervision; Christina D. George: Writing—Review and Editing; James R. Rodgers: Visualization; James P. Mauch, Nolan Barrette, David H. Malone, and Michael N. Sell: Investigation

REFERENCES

Antweiler, J.C., Love, J.D., Mosier, E.L., and Campbell, W.L., 1980, Oligocene gold-bearing conglomerate, southeast margin of Wind River Mountains, Wyoming, *in* Harrison, Avis, Glaze, Bob, Dietrich, Stan, Guy, Bill, Buckovic, Bill, Hollett, Doug, and Allen, Debbie, eds., Stratigraphy of Wyoming: Wyoming Geological Association, 31st annual field conference, Guidebook, p. 223–237.

Bailey, R.V., 1965, Applied geology in the Shirley Basin uranium district, Wyoming: Rocky Mountain Geology, v. 4, no. 1, p. 27–35.

Beebee, R.A., and Cox, Rónadh, 1998, Dynamics of marine transgression onto a non-linear shoreline—The Middle Cambrian Flathead Sandstone, Clarks Fork Valley, Wyoming: The Mountain Geologist, v. 35, no. 3, p. 91–101.

Beeler, H.C., 1908, Report on the Gold Standard placers on Little Big Horn River, Sheridan County, Wyoming: Office of the State Geologist [Wyoming State Geological Survey] Mineral Report 1908–103, 33 p.

Bell, L.H., 1970, Depositional history of the Cambrian Flathead Sandstone, Park County, Wyoming, *in* Enyert, R.L., ed., Symposium on Wyoming sandstones—Their economic importance—Past, present & future: Wyoming Geological Association, 22nd annual field conference, Guidebook, p. 115–131.

Bell, L.H., and Middleton, L.T., 1978, An introduction to the Cambrian Flathead Sandstone, Wind River Basin, Wyoming, *in* Boyd, R.G., Olson, G.M., and Boberg, W.W., eds., Resources of the Wind River Basin: Wyoming Geological Association, 30th annual field conference, Guidebook, p. 79–88.

Blackwelder, E., 1918, New geological formations in western Wyoming: Journal of the Washington Academy of Sciences, v. 8, no. 13, p. 417–426.

Borrowman, S.R., and Rosenbaum, J.B., 1962, Recovery of thorium from a Wyoming ore: U.S. Bureau of Mines Technical Report BM-RI-5917, 8 p., https://doi.org/10.2172/4803043.

Boyd, D.W., 1993, Paleozoic history of Wyoming, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., eds., Geology of Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Memoir 5, p. 164–187.

Cygan, N.E., and Koucky, F.L., 1963, The Cambrian and Ordovician rocks of the east flank of the Big Horn Mountains, Wyoming, *in* Cooper, G.C., Cardinal, D.F., Lorenz, H.W., and Lynn, J.R., eds., Northern Powder River Basin, Wyoming and Montana: Wyoming Geological Association, 18th annual field conference, Guidebook, p. 26–37.

Damp, J.N., and Brown, L., 1982, National uranium resource evaluation—Arminto quadrangle, Wyoming: U.S. Department of Energy Report PGJ/F-018(82), 512 p.

Damp, J.N., Jennings, M.D., and Brown, L., 1982, National uranium resource evaluation—Sheridan quadrangle, Wyoming and Montana: U.S. Department of Energy Report PGJ/F-127(82), 329 p.

Darton, N.H., 1906, Geology of the Bighorn Mountains: U.S. Geological Survey Professional Paper 51, 173 p., https://doi.org/10.3133/pp51.

Darton, N.H., and Salisbury, R.D., 1906, Bald Mountain-Dayton folio, Wyoming: U.S. Geological Survey Folios of the Geologic Atlas 141, 2 p., 7 pls., https://doi.org/10.3133/gf141.

Degenstein, Joel, 1978, Geology of the Flathead Formation (Middle Cambrian) on the perimeter of the Bighorn Basin, Beartooth Mountains, and Little Belt Mountains in Wyoming and Montana: Grand Forks, University of North Dakota, M.S. thesis, 164 p.

Denson, N.M., and Harshman, E.N., 1969, Map showing areal distribution of Tertiary rocks, Bates Hole—Shirley Basin area, south-central Wyoming: U.S. Geological Survey IMAP 570, scale 1:125,000, https://doi.org/10.3133/i570.

Dixon, H.R., 1990, Geologic map of the Seminoe Dam NE quadrangle, Carbon County, Wyoming: U.S. Geological Survey Geologic Quadrangle 1673, scale 1:24,000, https://doi.org/10.3133/gq1673.

Emry, R.J., 1973, Stratigraphy and preliminary biostratigraphy of the Flagstaff Rim area, Natrona County, Wyoming: Smithsonian Contributions to Paleobiology, v. 16, 43 p.

Ellis, J.R., 1977, Chemical and physical analyses of selected soil samples in Wyoming, 1967–1969: U.S. Department of Energy Report GJBX-45(77), 315 p.

Evanoff, Emmett, 1990, Early Oligocene paleovalleys in southern and central Wyoming: Evidence of high local relief on the late Eocene unconformity: Geology, v. 18, no. 5, p. 443–446, https://doi.org/10.1130/0091-7613(1990)018%3C0443:EOPISA%3E2.3.CO;2.

Garrand, L.J., Kopp, R.S., Cohenour, R.E., Damp, J.N., and Brown, L., 1982, National uranium resource evaluation—Cody quadrangle, Wyoming: U.S. Department of Energy Report PGJ/F-043(82), 418 p.

Gebhardt, Robert, Jennings, M.D., Fiscus, Dennis, Damp, J.N., and Brown, L., 1982, National Uranium Resource Evaluation: Lander Quadrangle, Wyoming: U.S. Department of Energy Report PGJ/F-050(82), 308 p.

Gersic, Joseph, Peterson, E.K., and Schreiner, R.A., 1990, Appraisal of selected mineral resources of the Black Hills National Forest, South Dakota and Wyoming: U.S. Bureau of Mines Mineral Land Assessment Open File Report MLA 5-90, 255 p.

Graff, P.J., and Houston, R.S., 1977, Radioactive conglomerate in Proterozoic (Precambrian X) metasedimentary rocks of the Sierra Madre, Wyoming: U.S. Geological Survey Open-File Report 77–830, 8 p., https://doi.org/10.3133/ofr77830.

Griffin, J.R., Milton, E.J., Damp, J.N., and Brown, L., 1982, National uranium resource evaluation—Casper quadrangle, Wyoming: U.S. Department of Energy Report PGJ/F-033(82), 613 p.

Harshman, E.N., 1972, Geology and uranium deposits, Shirley Basin area, Wyoming: U.S. Geological Survey Professional Paper 745, 82 p., https://doi.org/10.3133/pp745.

Hausel, W.D., 1989, The geology of Wyoming's precious metal lode and placer deposits: Geological Survey of Wyoming [Wyoming State Geological Survey] Bulletin 68, 248 p., 6 pls.

Hausel, W.D., 2006, Revised geologic map of the Miners Delight quadrangle, Fremont County, Wyoming: Wyoming State Geological Survey Map Series 38, scale 1:24,000.

Hausel, W.D., and Graves, W.H., 1996, Placers and paleoplacers of the Bighorn Basin, *in* Bowen, C.E., Kirkwood, S.C., and Miller, T.S., eds., Resources of the Bighorn Basin: Wyoming Geological Association, 47th annual field conference, Guidebook, p. 273–280.

Hausel, W.D., Marlatt, G.G., Nielsen, E.L., and Gregory, R.W., 1992, Preliminary study of precious metals and stones along the Union Pacific right-of-way of southern Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Mineral Report 92–1, 77 p., 1 pl.

Hausel, W.D., Marlatt, G.G., Nielsen, E.L., and Gregory, R.W., 1994, Study of metals and precious stones in southern Wyoming: Wyoming State Geological Survey Open File Report 94–2, 61 p., 1 pl.

Henderson, Paul, 1984, General geochemical properties and abundances of the rare earth elements, *in* Developments in geochemistry: Elsevier, p. 1–32., https://doi.org/10.1016/B978-0-444-42148-7.50006-X.

Houston, R.S., 1979, Introduction to the second uranium issue and some suggestions for prospecting: Rocky Mountain Geology, v. 17, no. 2, p. 85–88.

Houston, R.S., 1993, Late Archean and Early Proterozoic geology of southeastern Wyoming, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., eds., Geology of Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Memoir 5, p. 78–116.

Houston, R.S., Desborough, G.A., Karlstrom, K.E., Sharp, W.N., and Graff, P.J., 1979, Progress report on the study of radioactive quartz-pebble conglomerate of the Medicine Bow Mountains and Sierra Madre, southeastern Wyoming: U.S. Geological Survey Open-File Report 79–1131, 43 p., 2 pls., https://doi.org/10.3133/ofr791131.

Houston, R.S., Graff, P.J., Karlstrom, K.E., and Root, F., 1977, Preliminary report on radioactive conglomerates of Middle Precambrian age in the Sierra Madre and Medicine Bow Mountains of southeastern Wyoming: U.S. Geological Survey Open-File Report 77–574, 15 p., 2 pls., https://doi.org/10.3133/ofr77574.

Houston, R.S., and Karlstrom, K.E., 1979, Precambrian uranium-bearing quartz-pebble conglomerates—Exploration model and United States resource potential: U.S. Department of Energy Report GJBX-1, 510 p., 2 pls.

Houston, R.S., and Karlstrom, K.E., 1987, Application of the time and strata bound model for the origin of uranium bearing quartz-pebble conglomerate in southeastern Wyoming, USA, *in* Pretorius, Desmond, ed., Uranium deposits in Proterozoic quartz-pebble conglomerates: International Atomic Energy Agency IAEA-TECDOC-427, p. 99–131.

Houston, R.S., and Karlstrom, K.E., 1992, Geologic map of Precambrian metasedimentary rocks of the Medicine Bow Mountains, Albany and Carbon counties, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I–2280, 22 p., scale 1:24,000, https://doi.org/10.3133/i2280.

Hunter, J., Ver Ploeg, A.J., and Boyd, C.S., 2005, Geologic map of the Casper 30' x 60' Quadrangle, Natrona and Converse counties, central Wyoming: Wyoming State Geological Survey Map Series 65, scale 1:100,000.

Johnson, J.F., and Sutherland, W.M., 2009, Geologic map of the Lander 30' x 60' quadrangle, Fremont County, Wyoming: Wyoming State Geological Survey Map Series 87, 31 p., scale 1:100,000.

Jones, N.R., and Gregory, R.W., 2011, Preliminary geologic map of the Shirley Basin 30' x 60' quadrangle, Carbon, Natrona, Albany, and Converse counties, Wyoming: Wyoming State Geological Survey Open File Report 11–8, scale 1:100,000.

Karlstrom, K.E., 1977, Geology of the Proterozoic Deep Lake Group, central Medicine Bow Mountains, Wyoming: Laramie, University of Wyoming, M.S. thesis, 116 p.

Karlstrom, K.E., Flurkey, A.J., and Houston, R.S., 1983, Stratigraphy and depositional setting of the Proterozoic Snowy Pass Supergroup, southeastern Wyoming—Record of an early Proterozoic Atlantic-type cratonic margin: GSA Bulletin, v. 94, no. 11, p. 1,257–1,274, https://doi.org/10.1130/0016-7606(1983)94<1257:SADSOT>2.0.CO;2.

Karlstrom, K.E., and Houston, R.S., 1979a, Stratigraphy and uranium potential of Early Proterozoic metasedimentary rocks in the Medicine Bow Mountains, Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Report of Investigations 13, 45 p., 2 pls., scale 1:48,000.

Karlstrom, K.E., and Houston, R.S., 1979b, Stratigraphy of the Phantom Lake Metamorphic Suite and Deep Lake Group and a review of the Precambrian tectonic history of the Medicine Bow Mountains: Rocky Mountain Geology, v. 17, no. 2, p. 111–133.

Karlstrom, K.E., Houston, R.S., Schmidt, T.G., Inlow, David, Flurkey, A.J., Kratochvil, A.L., Coolidge, C.M., Sever, C.K., and Quimby, W.F., 1981, Drill-hole data, drill-site geology, and geochemical data from the study of Precambrian uraniferous conglomerates of the Medicine Bow Mountains and Sierra Madre of southeastern Wyoming: University of Wyoming [U.S. Department of Energy] National Uranium Resource Evaluation Report GJBX-139(81), 682 p., 2 pls., https://doi.org/10.2172/6759168.

King, J.K., 1991, Rare earth elements and yttrium in Wyoming: Wyoming State Geological Survey Industrial Minerals Report 91–3, 125 p. (Supersedes Geological Survey of Wyoming Open File Report 87-8; Revised by R.E. Harris 2002.)

Kline, M.H., and Winkel, W.W., 1952, Bald Mountain conglomerates (Deadwood Formation), Sheridan and Bighorn counties, Wyoming: U.S. Atomic Energy Commission Technical Report RMO-784, 14 p.

Larsen, J.H., 1964, Hanna, Laramie and Shirley Basins, *in* Highway geology of Wyoming: Wyoming Geological Association, p. 23–62.

Lillegraven, J.A., 1993, Correlation of Paleogene strata across Wyoming—A user's guide, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., eds., Geology of Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Memoir 5, p. 414–477.

Lillegraven, J.A., and Ostresh, L.M., 1988, Evolution of Wyoming's Early Cenozoic topography and drainage patterns: National Geographic Research, v. 4, p. 303–327.

Liu, S.L., Fan, H.R., Liu, Xuan, Meng, Jianyin, Butcher, A.R., Yann, Lahaye, Yang, K.F., and Li, X.C., 2023, Global rare earth elements projects—New developments and supply chains: Ore Geology Reviews, v. 157, p. 105,428, 10.1016/j.oregeorev.2023.105428.

Love, J.D., 1954, Reconnaissance for uranium in the United States—Wyoming, south rim of Bates Hole: U.S. Geological Survey [Atomic Energy Commission] Trace Elements Investigation Report TEI-440, 178–179 p.

Malan, R.C., 1972, Summary report—Distribution of uranium and thorium in the Precambrian of the western United States: U.S. Atomic Energy Commission Open-File Report AEC-RD-12, 59 p.

Malone, D.H., Craddock, J.P., and Kenderes, Stuart, 2017, Detrital zircon geochronology and provenance of the Middle Cambrian Flathead Sandstone, Park County, Wyoming: The Mountain Geologist, v. 54, no. 2, p. 86–103.

Mammone, Nicholas, Bekker, Andrey, Chamberlain, K.R., and Kuznetsov, A.B., 2022, Testing the early Paleoproterozoic connection of the Superior and Wyoming cratons with geochronology and geochemistry: Precambrian Research, v. 381, no. 106818, 29 p., 10.1016/j.precamres.2022.106818.

McKinney, A.A., and Horst, H.W., 1953, Deadwood Conglomerate monazite deposit Bald Mountain area, Sheridan and Big Horn counties, Wyoming: U.S. Bureau of Mines RME-3128, 40 p.

Middleton, L.T., 1980, Sedimentology of Middle Cambrian Flathead Sandstone, Wyoming: Laramie, University of Wyoming, Ph.D. dissertation, 198 p.

Middleton, L.T., Steidtmann, J.R., and DeBour, D.A., 1980, Stratigraphy and depositional setting of some Middle and Upper Cambrian rocks, Wyoming, *in* Harrison, Avis, Glaze, Bob, Dietrich, Stan, Guy, Bill, Buckovic, Bill, Hollett, Doug, and Allen, Debbie, eds., Stratigraphy of Wyoming: Wyoming Geological Association, 31st annual field conference, Guidebook, p. 23–35.

Miller, B.M., 1936, Cambrian stratigraphy of northwestern Wyoming: The Journal of Geology, v. 44, no. 2, p. 113–144, https://doi.org/10.1086/624413.

Miller, W.R., Houston, R.S., Karlstrom, K.E., Hopkins, D.M., and Ficklin, W.H., 1977, Geological and geochemical investigations of uranium occurrences in the Arrastre Lake area of the Medicine Bow Mountains, Wyoming: U.S. Geological Survey Open-File Report 77–92, 30 p., https://doi.org/10.3133/ofr7792.

Pierce, W.G., 1966, Geologic map of the Cody quadrangle, Park County, Wyoming: U.S. Geological Survey Geologic Quadrangle 542, scale 1:62,500, https://doi.org/10.3133/gq542.

Roehler, H.W., 1958, Geology of Bates Hole, Wyoming: Laramie, University of Wyoming, M.A. thesis, 58 p.

Rohrer, W.L., 1968, Geologic map of the Fish Lake quadrangle, Fremont County, Wyoming: U.S. Geological Survey Geologic Quadrangle 724, scale 1:24,000, doi: https://doi.org/10.3133/gq724.

Rudnick, R., and Gao, S., 2014, Composition of the continental crust: Treatise on geochemistry, v. 4, p. 1–51, https://doi.org/10.1016/B978-0-08-095975-7.00301-6.

Sando, W.J., and Sandberg, C.A., 1987, New interpretations of Paleozoic stratigraphy and history in the northern Laramie Range and vicinity, Southeast Wyoming: U.S. Geological Survey Professional Paper 1450, 39 p., 2 pls., https://doi.org/10.3133/pp1450.

Sell, M.N., 2022, Geology, geochronology, and preliminary rare-earth element (REE) occurrence in the Bald Mountain 7.5-minute quadrangle, north central Wyoming, USA: Normal, Illinois State University, M.S. thesis, 77 p., https://doi.org/10.30707/ETD2022.20220705065054196065.999967.

Sell, M.N., Krieger, Aidan, Huisman, Matthew, and Malone, David, 2023, Geologic map of the Bald Mountain quadrangle, northern Bighorn Mountains, Wyoming: The Mountain Geologist, v. 60, no. 1, p. 21–46.

Sims, P.K., Finn, C.A., and Rystrom, V.L., 2001, Preliminary Precambrian basement map showing geologic-geophysical domains, Wyoming: U.S. Geological Survey Open-File Report 2001–199, 9 p., 2 pls., https://doi.org/10.3133/ofr01199.

Stipp, T.F., 1947, Paleozoic formations near Cody, Park County, Wyoming: AAPG Bulletin, v. 31, no. 2, p. 274–281.

Stuckless, J.S., and Nkomo, I.T., 1978, Uranium-lead isotope systematics in uraniferous alkali-rich granites from the Granite Mountains, Wyoming—Implications for uranium source rocks: Economic Geology, v. 73, no. 3, p. 427–441, https://doi.org/10.2113/gsecongeo.73.3.427.

Stueber, A.M., and Heimlich, R.A., 1977, Rb-Sr isochron age of the Precambrian basement complex, Bighorn Mountains, Wyoming: GSA Bulletin, v. 88, no. 3, p. 441–444, https://doi.org/10.1130/0016-7606(1977)88<441:RIAOTP>2.0.CO;2.

Sutherland, W.M., and Cola, E.C., 2015, Iron resources in Wyoming: Wyoming State Geological Survey Report of Investigations 67, 92 p.

Sutherland, W.M., and Cola, E.C., 2016, A comprehensive report on rare earth elements in Wyoming: Wyoming State Geological Survey Report of Investigations 71, 137 p.

Sutherland, W.M., Gregory, R.W., Carnes, J.D., and Worman, B.N., 2013, Rare earth elements in Wyoming: Wyoming State Geological Survey Report of Investigations 65, 82 p.

Sutherland, W.M., and Hausel, W.D., 2005, Geologic map of Barlow Gap quadrangle, Natrona County, Wyoming: Wyoming State Geological Survey Map Series 67, scale 1:24,000.

Thaden, R.E., 1978, Geologic map of the Bonneville quadrangle, Fremont County, Wyoming: U.S. Geological Survey Geologic Quadrangle 1439, scale 1:24,000, https://doi.org/10.3133/gq1439.

Thomas, H.D., 1948, Summary of Paleozoic stratigraphy of the Wind River Basin, Wyoming, *in* Maebius, J.B., and Netterstrom, P.W., eds., Wind River Basin, Wyoming: Wyoming Geological Association, 3rd annual field conference, Guidebook, p. 79–95.

Thomas, H.D., 1949, Summary of Paleozoic stratigraphy of the Powder River Basin, *in* Jenkins, P.T., ed., Powder River Basin: Wyoming Geological Association, 4th annual field conference, Guidebook, p. 40–45.

Thomas, H.D., 1950, Summary of the Paleozoic stratigraphy of the Green River Basin, Wyoming, *in* Harrison, J.W., ed., Southwest Wyoming: Wyoming Geological Association, 5th annual field conference, Guidebook, p. 17–24.

Thomas, H.D., 1951, Summary of Paleozoic stratigraphy of the region about Rawlins, South-Central Wyoming, *in* Brinker, W.F., and Blackstone, D.L., Jr., eds., South Central Wyoming: Wyoming Geological Association, 6th annual field conference, Guidebook, p. 32–36.

U.S. Department of the Interior, 2018, Final list of critical minerals 2018: Federal Register 2018–10667, 23295–23296 p.

U.S. Geological Survey, 2022, 2022 final list of critical minerals: Federal Register 2022–04027, 10381–10382 p.

Van Gosen, B.S., Verplanck, P.L., Seal, R.R., Long, K.R., and Gambogi, Joseph, 2017, Rare-earth elements: U.S. Geological Survey Professional Paper 1802-O, 44 p., https://doi.org/10.3133/pp1802O.

Vine, J.D., and Denson, N.M., 1954, U.S. Atomic Energy Commission Preliminary Reconnaissance Report F-1141, 1 p.

Whalen, J.F., 1954, U.S. Atomic Energy Commission Preliminary Reconnaissance Report DEB-RRD-1390, 1 p.

Wilson, W.H., 1951, A monazite deposit in the Big Horn Mountains, Sheridan and Big Horn counties, Wyoming: Geological Survey of Wyoming [Wyoming State Geological Survey] Mineral Report 51–6, 3 p.

Wilson, W.H., 1960, Radioactive mineral deposits of Wyoming: Wyoming State Geological Survey Report of Investigations 7, 41 p.

Appendices

APPENDIX 1: SAMPLE LOCATIONS AND METADATA

Sample locations and metadata are given in file *Appendix1_sample_locations_and_metadata.csv*. The "|" character is used to separate multiple values for fields "Locale_Name_Alt" and "Geologic_Unit". Latitude and longitude are reported in WGS84. TRUE and FALSE are represented as integer 1 and 0, respectively.

APPENDIX 2: MAJOR-ELEMENT OXIDE GEOCHEMISTRY

Major-element oxide geochemistry results are given in file *Appendix2_geochem_oxides.csv*.

APPENDIX 3: ELEMENTAL GEOCHEMISTRY

Elemental geochemistry results are given in file *Appendix3_geochem_elemental.csv*.

APPENDIX 4: BULK-MINERAL ANALYSIS

Results of bulk-mineral mineral analysis with QEMSCAN® are given in files *Appendix4-1_mineral_composition_bulk_mineral_analysis.csv*, *Appendix4-2_Ti_deportment_bulk_mineral_analysis.csv*, *Appendix4-3_Si_deportment_bulk_mineral_analysis.csv*, and *Appendix4-4_assays_bulk_mineral_analysis.csv*.

Notes to accompany Appendix 4-1

1) Other sulphide minerals includes galena, sphalerite, molybdenite and trace nickel cobalt sulphides.

2) Sulphate minerals includes calcium sulphate, jarosite, barite, and alunite.

3) Iron oxides includes goethite/limonite and trace magnetite, hematite, and steel.

4) Feldspars includes K feldspar, feldspar albite (Na feldspar), and minor amounts of calcium plagioclase feldspar.

5) Calcium carbonates includes calcite, dolomite, and ankerite.

6) Titanium minerals includes rutile/anatase, Ti-hematite, ilmenite, TiFeO, and TiSiO.

7) Kandite group includes kaolinite (clay).

8) Others includes trace amounts of Ce-phosphate (monazite), epidote, garnets, and other unresolved mineral species.

9) A particle mineral analysis was used for the data.

10) All values are expressed as a percent.

11) Measurement was scanned on the QEMSCAN®.

12) The samples are fine grained and some particles occur as clumps so the mineral composition should be considered an estimate.

Notes to accompany Appendix 4-2

1) Other titanium-bearing minerals includes ilmenite, TiFeO, and TiSiO.

Notes to accompany Appendix 4-3

1) Feldspars includes K feldspar, feldspar albite (Na feldspar), and minor amounts of calcium plagioclase feldspar.

2) Titanium minerals includes a TiSiO.

3) Other silicate minerals includes kaolinite (clay), garnets, and epidote.