Rare Earth Element Concentrations in the Harmon, Hanson, and H Lignites in Slope County, North Dakota

by

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Abstract

Twenty geologic sections were measured along the steep cliff faces near Tepee Buttes on Logging Camp Ranch in Slope County, North Dakota. A total of 113 samples were collected and analyzed for rare earth element concentrations. The majority of these samples were lignite coming from the Harmon, Hanson, and H beds in the Bullion Creek Formation of the Fort Union Group (Paleocene). Samples were collected from three main areas, 94 samples came from the measured sections north of the Little Missouri River and 19 samples were obtained from two localities on the south side of the river first reported by Kruger and others (2017). Rare earth concentrations at the top of the Harmon bed averaged 112 ppm on the north side of the river, but averaged 314 ppm on a whole rock basis in section 7 on the south side of the river.

Samples from the top of the H bed, two on the north side of the river and one on the south side had rare earth element whole rock analysis of 171, 638, and 1,026 ppm. The rare earth element concentrations of 638 and 1,026 ppm are the highest values yet reported from North Dakota lignite.

Acknowledgements

We wish to thank the Hanson family, Robert and Ann & John and Jennifer, for allowing us access to the rock outcrops on Logging Camp Ranch and for their hospitality. In addition, we obtained a collecting permit from the U.S. Forest Service for sections 6, 7, and 8 and were assisted in that process by Tina Thornton and Sabry Hanna. Joseph Hartman, University of North Dakota, provided a copy of measured section number 56 from Belt and others (2004).

Introduction

A previous North Dakota Geological Survey study (Kruger et al., 2017) collected lignite, carbonaceous mudstone, and carbonaceous claystone samples for rare earth element analyses from 65 sites, most of which lie within a 1,875 square mile (4,856 square km) study area in western North Dakota. Sixteen of the 65 sample sites contained samples with rare earth concentrations of 300 parts per million (ppm) or greater (Figure 1). Five of those sites are located within the Logging Camp Ranch in Slope County. At one location (containing sample sites 56-58), the top of a lignite (the Harmon bed) contains rare earth element concentrations up to 555 ppm and is overlain by terrace gravels. At another location 1.9 miles (3.1 km) to the east (sample sites 54 and 55), a thin lignite (the H bed) is overlain by sandstone and contains rare earth concentrations up to 603 ppm (Kruger et al., 2017).

The current study incorporated both of the Kruger and others (2017) Logging Camp Ranch localities as well as an extensive area one mile (1.6 km) to the north. Three Paleocene coals or coal zones, the Harmon, Hanson, and H beds, were the primary sample targets in this study. The Harmon bed is the thickest, most extensive lignite in North Dakota (Figure 2). It reaches a maximum thickness of 53 feet (16.2 m) and extends over an area of approximately 13,000 square miles (33,670 square km) in western North Dakota (Murphy et al., 2002; Murphy, 2012). Throughout a portion of its lateral extent, the Harmon bed is underlain by the Hanson bed and the Hanson is in turn underlain, more locally, by the H bed of Hares (1928).

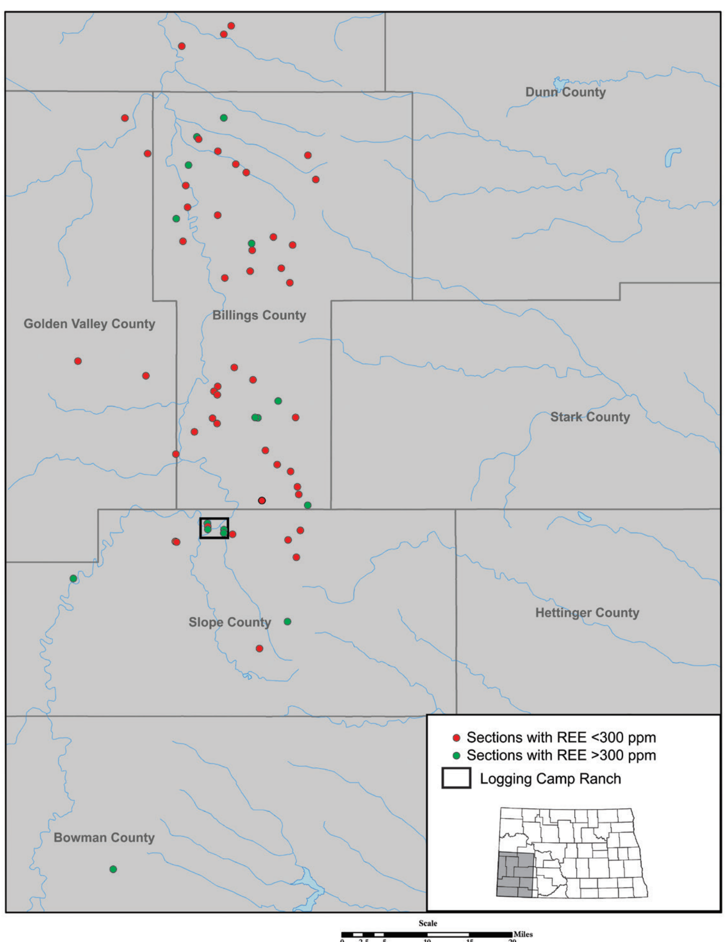


Figure 1. The sample locations (dots) for the Kruger and others (2017) study.

All rare earth concentrations in this report are reported on a whole rock basis, unless otherwise noted.

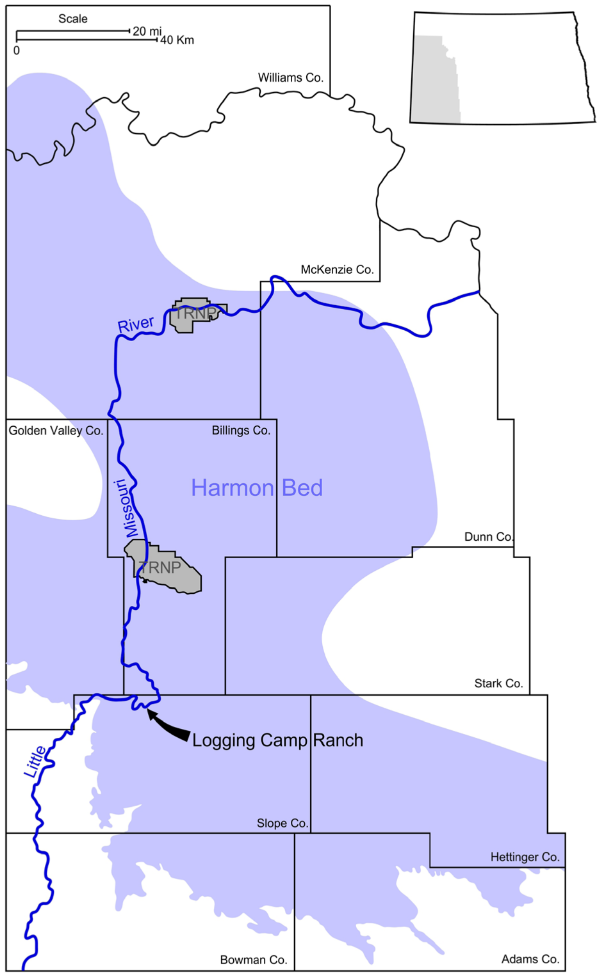


Figure 2. Extent of the Harmon bed and location of the Logging Camp Ranch. Modified from Murphy et al. (2002).

Logging Camp Ranch Study Area

The Logging Camp Ranch was chosen for study because of the high rare earth concentrations found in the previous study and the 1.5-miles (2.4 km) of nearly continuous outcrops of Bullion Creek strata in vertical to near-vertical, 100 to 400 foot (30-122 m) high cliff faces adjacent to the Little Missouri River (Figure 3). Across this 1.5 mile transect, Bullion Creek strata is variably overlain by Quaternary terrace gravels, and the Harmon, Hanson, and H bed, as well as other lignites, are often overlain by sandstone. Kruger and others (2017) hypothesized the permeability of overlying strata may play a role in rare earth transport after observing slightly elevated average rare earth concentrations in coals beneath sandstone. The authors also noted terrace gravels in the area contain clasts derived from the White River Group, a unit which contains a significant volcanogenic component hypothesized as a source of the rare earths found in underlying lignites.

The Logging Camp Ranch and the HT Ranch were famous ranches established in the 1880s by the Little Missouri Horse Company with A.C. Huidekoper as president. The ranches raised thousands of horses that were halter broke and shipped to Pennsylvania for training before being sold to entities such as the Knickerbocker Ice Company in New York (Roberts, 1976). William Henry Hanson came to North Dakota in 1904 and lived at the Logging Camp Ranch while working for A.C. Huidekoper. Hanson stayed on at the ranch after it was sold in 1909, first to Fred Pabst of the Pabst Brewing Company and then to I.P. Baker (Kopseng, 1976). The Hanson family eventually purchased the Logging Camp Ranch on which four generations have now lived (Murphy, 2002).

Previous Work

The Harmon, Hanson, and H lignite beds, located in the lower Bullion Creek Formation, are exposed in outcrop throughout much of the Logging Camp Ranch. In the 1908 biennial report of the North Dakota Geological Survey, A.G. Leonard named three consecutive coals exposed along the valley of the Little Missouri River south of Bullion Butte, in ascending order; beds G, H, and I (Leonard, 1908). He placed these beds in the "Great Bend Group" of the Fort Union Formation, as the three coals are prominently exposed along a thirty mile (48 km) stretch of the north-flowing Little Missouri River where it bends around Bullion Butte (from the old Yule site in Golden Valley County to the mouth of Garner Creek in Billings County). Leonard measured 584 feet of

Figure 3. Extensive outcrops of Bullion Creek strata at Logging Camp Ranch, Slope County, North Dakota. Photo taken looking north/northwest from the sw/sw of section 8 (T136N, R102W). Tepee Buttes are located near the west edge of the photograph.

Bullion Creek strata at Tepee Buttes, a set of small peaks just north of the Little Missouri River at Logging Camp Ranch. He lists the location of his measured section as the southwest quarter of section 5 (T136N, R102W). The base of his measured section would have been in section 5, but the top would have been in the southeast quarter of section 6.

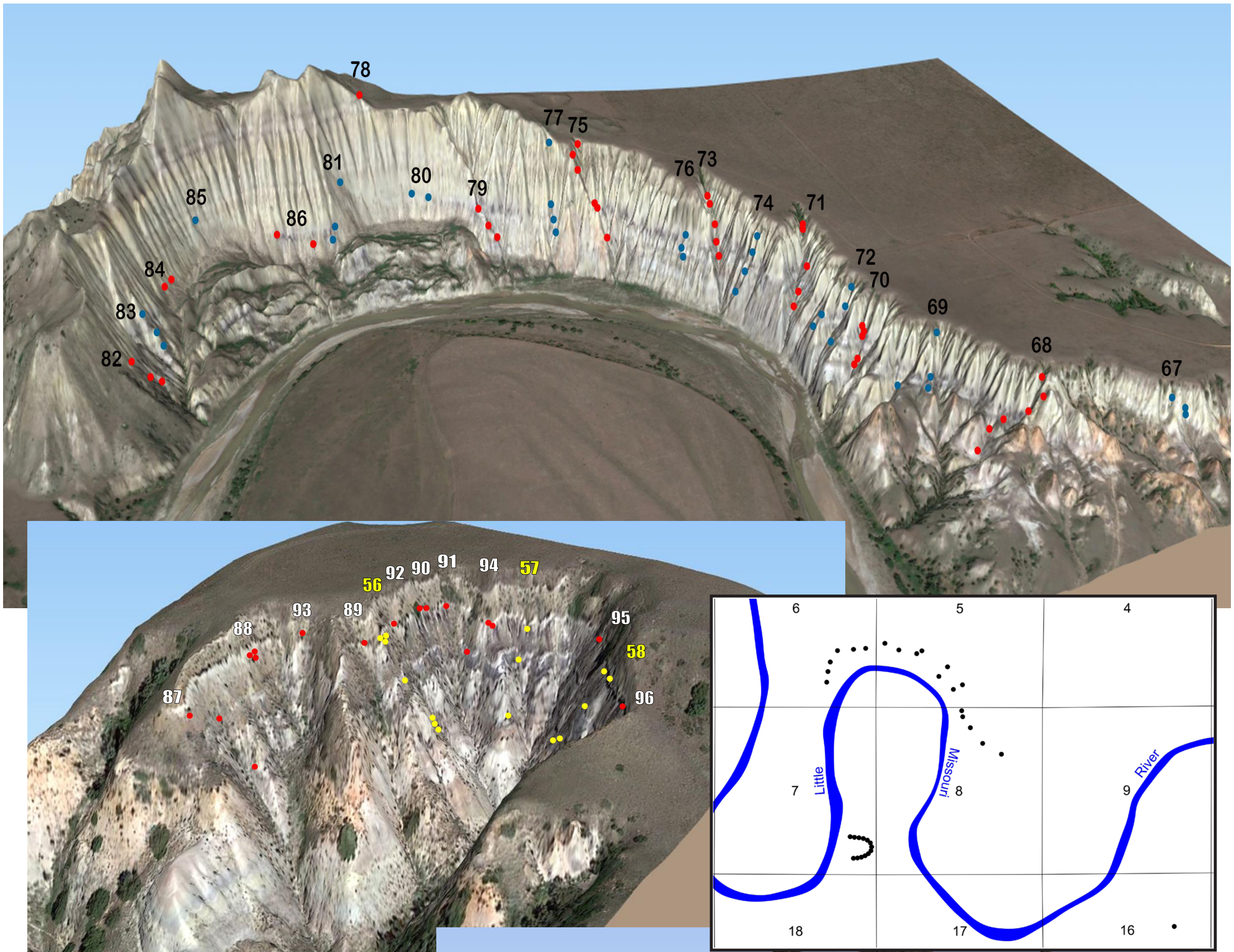
In 1928, C.J. Hares reported on the lignite resources in an area from the Montana border to the town of Bowman and from the South Dakota line almost to Medora. He renamed Leonard's bed I the Harmon bed, after he determined that it correlated to the Harmon coal that Leonard and Smith (1907) had named in the Medora area. In addition, Hares applied the name "Hansen bed" to a thick lignite (Leonard's H bed) that occurs below, and in this area in close proximity to, the Harmon bed. Typical of the time, many coals were named for ranches in the vicinity of major outcrops or after the small workings from which they were mined. Murphy (2002) did a search of the U.S. Bureau of Land Management General Land Office records and found a few Hansens in Slope and Bowman counties at, or around, the time that Hares was doing his fieldwork (1911 and 1912), but none of these Hansens resided within the Hares study area. Murphy also determined that W.H. Hanson and his sons John and Robert were living within Hares' study boundaries in areas that contained prominent outcrops of this thick coal bed. Based upon that information, he surmised that Hares had inadvertently misspelled the family name. As a result, from 2002 on, the NDGS has been referring to that coal as the Hanson bed. Hares also renamed Leonard's bed G, the H bed.

Brant (1953) followed Hares nomenclature and used the Harmon, "Hansen," and H beds in his report on the lignite resources of North Dakota. Brant noted that he did little fieldwork and relied on the data in Leonard (1908), Hares (1928), and other published reports on North Dakota lignites. Peter Warwick (1982) measured 96 geologic sections in the Bullion Creek Formation (mapped as Tongue River) from Medora south to Bullion Butte. Two of those measured sections fall within the Tepee Buttes area (Warwick and Luck, 1995). Warwick and others (1995), investigating parasequences in the lower Fort Union Group, determined the age of a tonstein in the H bed (the Hanson bed of this report) at Logging Camp Ranch at 61.23 + 0.38 million years ago. Murphy and others (1999, and 2000) correlated the Harmon and Hanson beds in the subsurface in [Golden Valley, Billings, Stark, Slope, Adams, Bowman, and Hettinger] counties. There was little subsurface control in and around Logging Camp Ranch; three geophysical logs through the Fort Union Group were reported in T136N, R102W and only 17 additional logs in the surrounding townships. Warwick and others (2004) correlated 18 measured sections across southwestern North Dakota and northwestern South Dakota generating five palynologic biozones. One of the measured sections (no. 10) was at the Logging Camp Ranch and 22 rock samples from that section were analyzed for fossil pollen (note the location of the "H coal" tonstein in Table 2 of Warwick and others (2004) should be Lat. 46.6083333^{o}, Long. -103.518667^{o}). Reporting on unconformities and age relationships between the Bullion Creek Formation and older strata in the Fort Union Group, Belt and others (2004) presented one measured section (B56) at Logging Camp Ranch and gave an age of 61.06 + 0.33 million years ago for the H bed (the Hanson bed of this report) tonstein, adding support to the age determination of Warwick and others (1995) for that same tonstein in a locality 250 feet (76 m) to the northwest.

Fieldwork

A total of 113 coal and carbonaceous claystone samples were collected from three localities and analyzed for rare earth element concentrations during this project. Ninety-four samples were collected along a 1.5 mile (2.4 km) long northwest-southeast transect ending just west of Tepee Buttes from September 11-14, 2017 (sections 5, 6, and 8, T136N, R102W) (Figure 4). An additional 17 samples were collected adjacent to Kruger and others (2017) measured sections 56, 57, and 58 in October and November 2017 (SESE section 7, T136N, R102W) (Figure 4). Two samples were collected from the H bed midway between Kruger and others (2017) measured sections 54 and 55 (ne section 16, T136N, R102W) (Figure 4). The top of the Harmon bed was sampled at 18 of the 20 sections that were measured on the north side of the Little Missouri River. The Hanson and H beds were also sampled when they were exposed. Measured sections 67-86 were spaced an average of 450 feet (137 m) apart compared to the 4.5 mile (7.2 km) section spacing for the Kruger and others (2017) project. Sections could not always be evenly spaced due to inaccessibility. Of the 113 samples, 49 were collected from the Harmon bed, 16 from the Hanson bed, four from the H bed, and 44 samples from a dozen or so thin coals and carbonaceous claystones located primarily above the Harmon bed.

A number of events combined to make this an extremely physically challenging field project. The air temperature was uncharacteristically hot with several days in the 90s (>32 C), one of



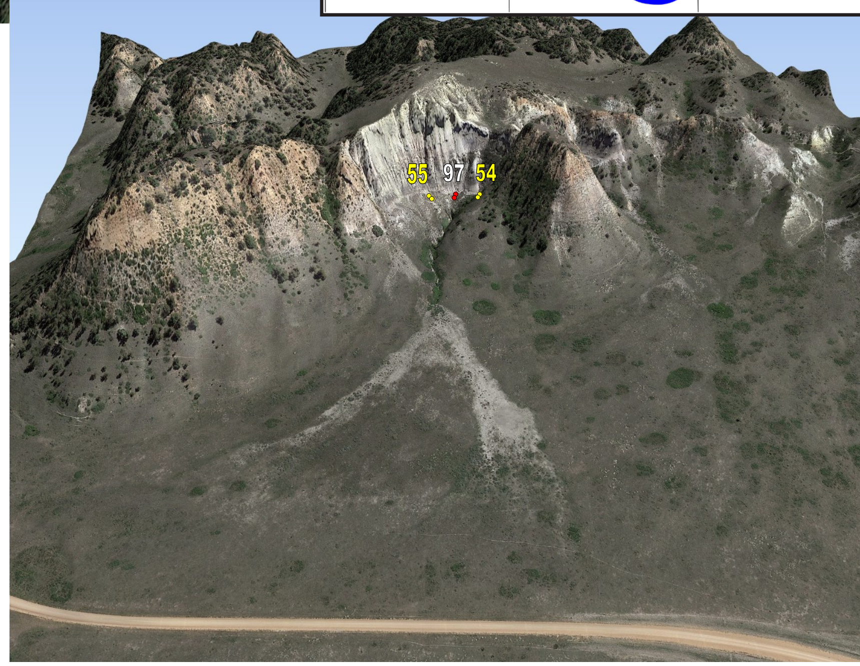


Figure 4. Top: The sample locations (dots) in sections 5, 6, and 8 (T136N, R102W) plotted on a GoogleEarth image. The samples are color coded by measured section. Note the prominent landslide material below sections 79 – 86. Center: The sample locations (dots) in section 7 (T136N, R102W) plotted on a GoogleEarth image. The yellow dots were sampled by Kruger and others (2017) and the red dots represent those samples collected for this study. Bottom: Sample locations in section 16 (T136N, R102W) plotted on a GoogleEarth image. The yellow dots were sampled by Kruger and others (2017), the red dots this study.

which (September 12) reached 100 F (37.8 C). The field party was forced to ascend or descend through steep ravines due to the near vertical cliff faces (Figure 5). The exposed rocks range from extremely soft (e.g., poorly cemented siltstones) to well indurated or cemented (e.g., well cemented sandstone concretions). Excavated hand holes and foot holes routinely gave way in the soft strata or at times were extremely difficult to excavate in the highly indurated or well cemented rock. Along the western portion of the field area (measured sections 80-86) the majority of the slopes were inaccessible without climbing gear due to the steep terrain. Colluvial fans were ascended at measured sections 80 and 85 in order to access the outcrops (Figures 6 and 7). When possible, the field party of four followed narrow game trails made by deer or bighorn sheep. Thick smoke from forest fires in western Montana and Alberta, Canada added to the difficulties and the field party was forced to wear dust masks to combat the high volume of particulates in the air (Figure 8). The ND Department of Health issued a statement on September 13 warning of exposure to the smoke and the U.S. EPA designated air quality for the area as “unhealthy.” On the positive side, there was little slope wash on the steep slopes and many of the Harmon, Hanson, and H bed outcrops were fresh, often requiring only half of the standard one-foot (0.31 m) excavation (Figure 9).

Laboratory Procedures

Standard Laboratory in Casper, Wyoming prepared 94 of the samples and Standard Laboratory in Freeburg, Illinois performed the rare earth element analysis on the samples. Those samples were analyzed using a Perkin Elmer NexION 300x Inductively Coupled Plasma Mass Spectrometry

Figure 5. The ravine in the center of the photograph was ascended to measure geologic section no. 77 and to collect samples.

Figure 6. The cliff face beneath Tepee Buttes. It is a distance of almost 400 feet (122 m) from the top of Tepee Buttes to the base. The field party was only able to ascend to the top of the prominent colluvial fan (right of center in this drone photograph -- north) due to the steep terrain to collect samples 85b and 85f. The uneven ground at the base of the cliffs is landslide material.

Figure 7. Levi Moxness collecting sample 85b and Ned Kruger collecting sample 85f after ascending a colluvial fan. This spot, 70 feet (21 m) above the floor, marked the prudent limit of ascension at this locality in the absence of climbing gear.

Figure 8. Thick smoke from forest fires in Montana and Canada envelops the field area on the afternoon of September 12, 2017. The Harmon coal is exposed in the foreground adjacent to measured section no. 74. Photo looking southeast along the Little Missouri River.

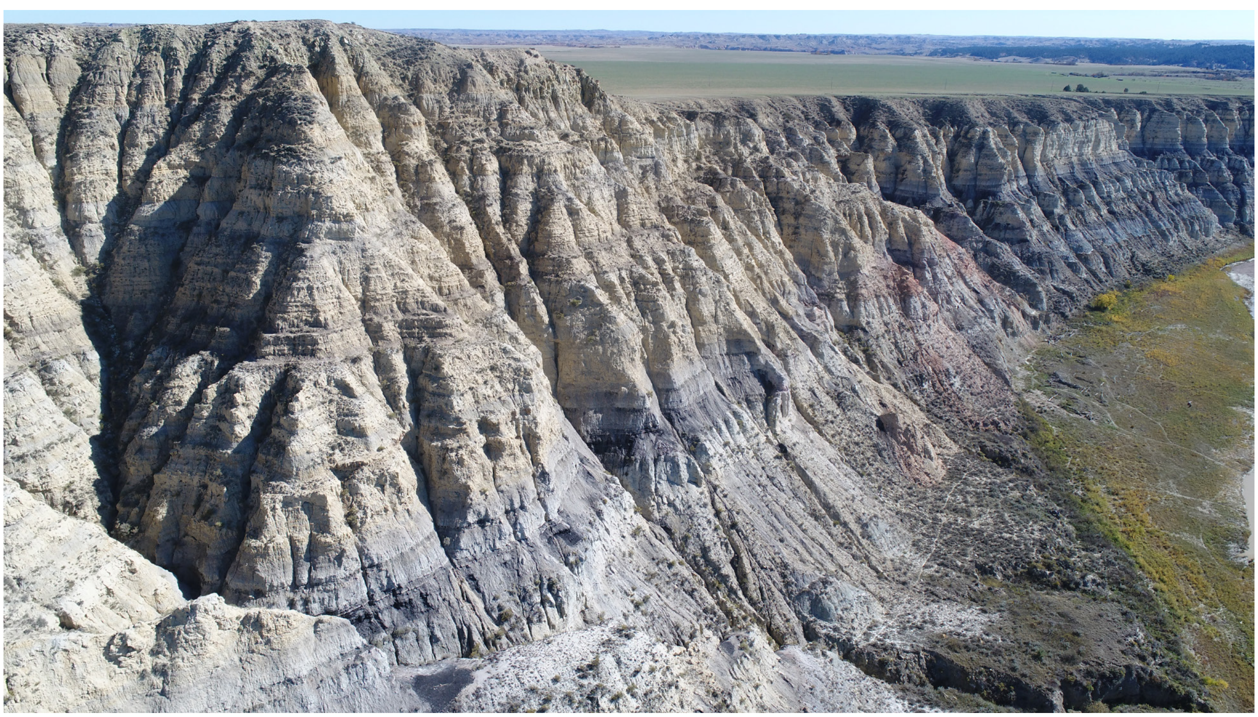


Figure 9. Rocks of the Bullion Creek Formation are well exposed along the steep cliff faces in the Tepee Buttes area. This drone photograph, taken looking southeast, encompasses measured sections 73-80. The flat-lying ancestral Little Missouri River terrace is visible throughout much of this photo. The terrace is underlain by windblown silts and terrace gravels.

(ICP-MS). American Society for Testing and Materials (ASTM) standards and specifications D6357 does not list rare earth elements, but does note the method is applicable to other elements. Eleven different known value standards were analyzed in order to verify the analytical technique; five NIST known values (1632D, 1633b, 1633c, 2702, and 2711), two SARM known values (18 and 19), and four USGS known values (AGV-2, BHVO-1, MAG-1, and SGR-1). Concentrations were reported on both a whole coal and ash basis for cerium, dysprosium, erbium, europium, gadolinium, holmium, lanthanum, lutetium, neodymium, praseodymium, samarium, scandium, terbium, thulium, ytterbium, and yttrium.

The Energy and Environmental Research Center at the University of North Dakota in Grand Forks, ND analyzed 19 of the samples. Splits of the as-received samples were dried in a convection oven at 30°C to constant weight according to ASTM method D3302. The dried samples were ground and riffled according to ASTM methods (D2234/D2013), the final particle size was 75µm (-200 mesh screen). Moisture and ash content were determined on the analysis sample according to ASTM methods D3173 and D3174, although the ashing temperature was reduced to 550°C. The total moisture in the as-received sample was determined by combining the moisture loss at 30°C with that determined at 105°C. REE analyses of materials was performed through digesting and analysis using ASTM Method D4503 including inductively coupled plasma–mass spectrometry (ICP–MS). All samples were dried at 105°C and ignited at 550°C prior to digestion and mass losses were recorded to enable elemental results to be reported on a dry whole sample or dry whole mineral basis. Using a 1:6 sample-to-flux ratio as prescribed in ASTM D4503, samples were digested with a 65/35 mixture of lithium metaborate/lithium tetraborate by heating in graphite crucibles at 1000°C until fully decomposed. The resultant glass beads were dissolved in 5% (v/v) nitric acid and diluted by 50× to reduce matrix interferences from the high total dissolved solids. A Thermo Scientific Model iCAP Q was used for the ICP–MS analysis.

Tepee Buttes Section

The alternating sandstones, siltstones, mudstones, claystones, lignites, and clinkers of the Bullion Creek Formation (Paleocene) are the prominent rocks in and around the Logging Camp Ranch (Figure 10). Five miles (8 km) to the northwest, Bullion Butte is capped by rocks of the Chadron and Golden Valley Formations (Eocene) and underlain by several hundred feet (>75 m) of rocks of the Sentinel Butte Formation (Murphy et al., 1993). Approximately 350 feet (107 m) of Bullion Creek strata is exposed on the south-facing slopes along the western edge of the study area (Figure 10). Exposures thin to less than 50 feet (15.2 m) along the eastern edge of the study area in the northeast quarter of section 8. The thickest sections measured in this study (sections 75 and 77) are approximately 270 feet (82.3 m) thick and the thinnest section (section 67) is 85 feet (25.9 m) thick. Landslide material at the base of the slopes beneath Tepee Buttes covers outcrops to an elevation of 2,570 feet (783.3 m). The landslide material and overlying colluvial fans/aprons obscure the Harmon and Hanson beds between measured sections 84 and 86 (Figure 10).

The Bullion Creek Formation is overlain by terrace gravels deposited by the ancestral Little Missouri River in the eastern two-thirds of the study area. The poorly sorted, brown, sandy gravel is 5-15 feet (1.5-4.6 m) thick and is comprised of pebbles and cobbles of chert, silcrete, ironstone, quartzite, volcanic porphyries, and fossil wood. Occasionally, the gravel is incased in iron cement. In places, the gravel is overlain by up to 15 feet (4.6 m) of loess (Figure 10).

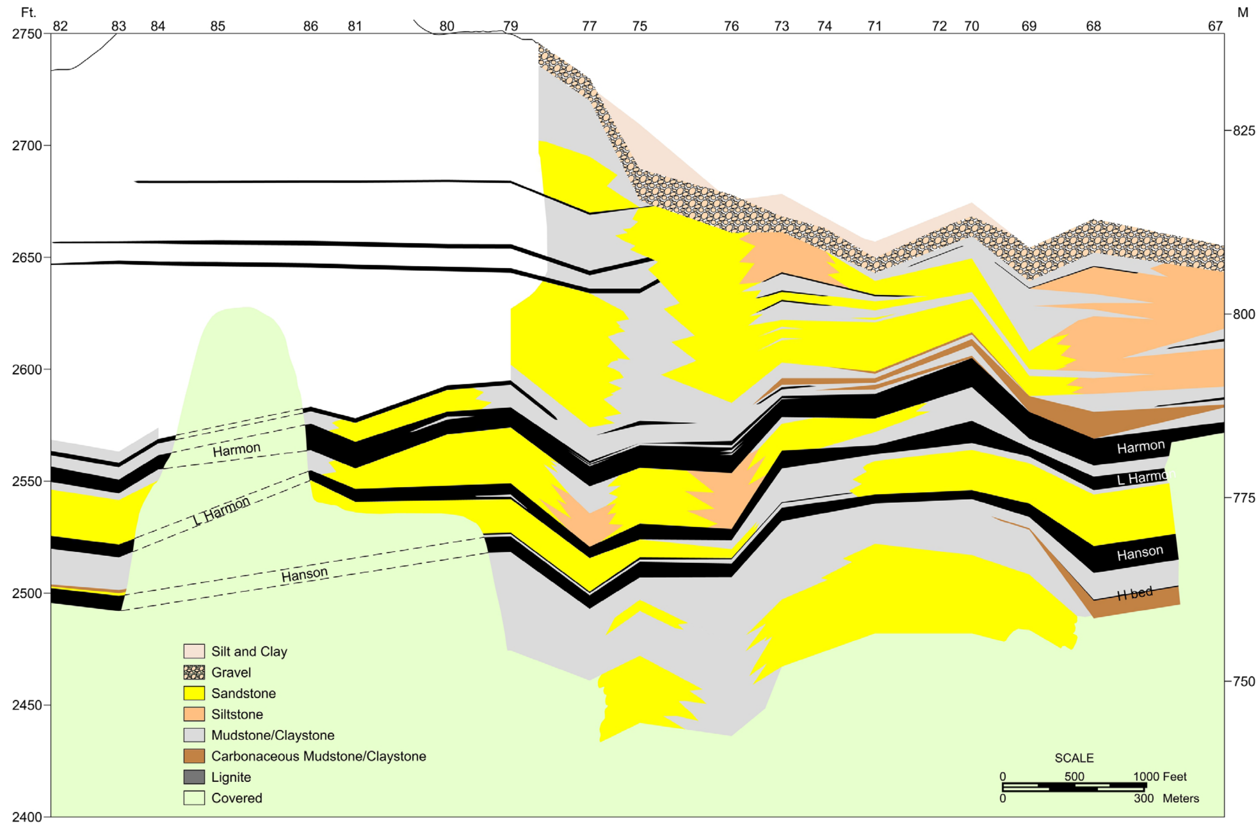


Figure 10. A stratigraphic cross-section through the study area. Landslide material obscures the Harmon bed beneath Tepee Buttes and rocks were too steep along the western portion of the cross section to enable sections to be measured to the top of the cliffs.

Coal Correlation

Six publications (Leonard, 1908; Hares, 1928; Warwick, 1982; Warwick and Luck, 1995; Belt et al., 2004; and Warwick et al., 2004) have each reported a geologic section that plots between measured section nos. 69 and 79 of this report (Figure 11). All six appear to agree that the three successive thick coals that can be correlated through the study area are the Harmon, Hanson, and H beds (Leonard's original I, H, and G beds respectively). Doing so makes the H bed thicker than the Hanson through much of the area. A cross section compiled of measured sections from these previous studies, as well as this study, demonstrates that there are at least two interpretations of coal correlation in the Logging Camp area (Figures 12 and 13). An alternate interpretation is that the Harmon bed splits in this area and the three successive thicker (>5ft, >1.5 m) coals are instead the Harmon, lower Harmon, and the Hanson (Figure 13). The H bed, which Hares identified as a 20-inch-(51 cm)-thick lignite in measured section no. 264 (T136N, R102W, sec. 16), appears to thin into a carbonaceous layer and disappear on the north side of the Little Missouri River (Figures 10 and 13). This is not unusual, as Fort Union lignites can thin, thicken, and split over relatively short distances, and thin beds are especially difficult to correlate due to their limited lateral extent. That is why coals are best correlated as stratigraphic packages bounded by coals, especially in the subsurface or at the surface in areas of limited outcrop control (Murphy, 2006). Hares' section no. 264 is 4,000 feet (1,219 m) south of an isolated outcrop (Hares' section no. 251) and roughly 8,000 feet (2,438 m) south of extended areas of outcrops on the north side of the Little Missouri

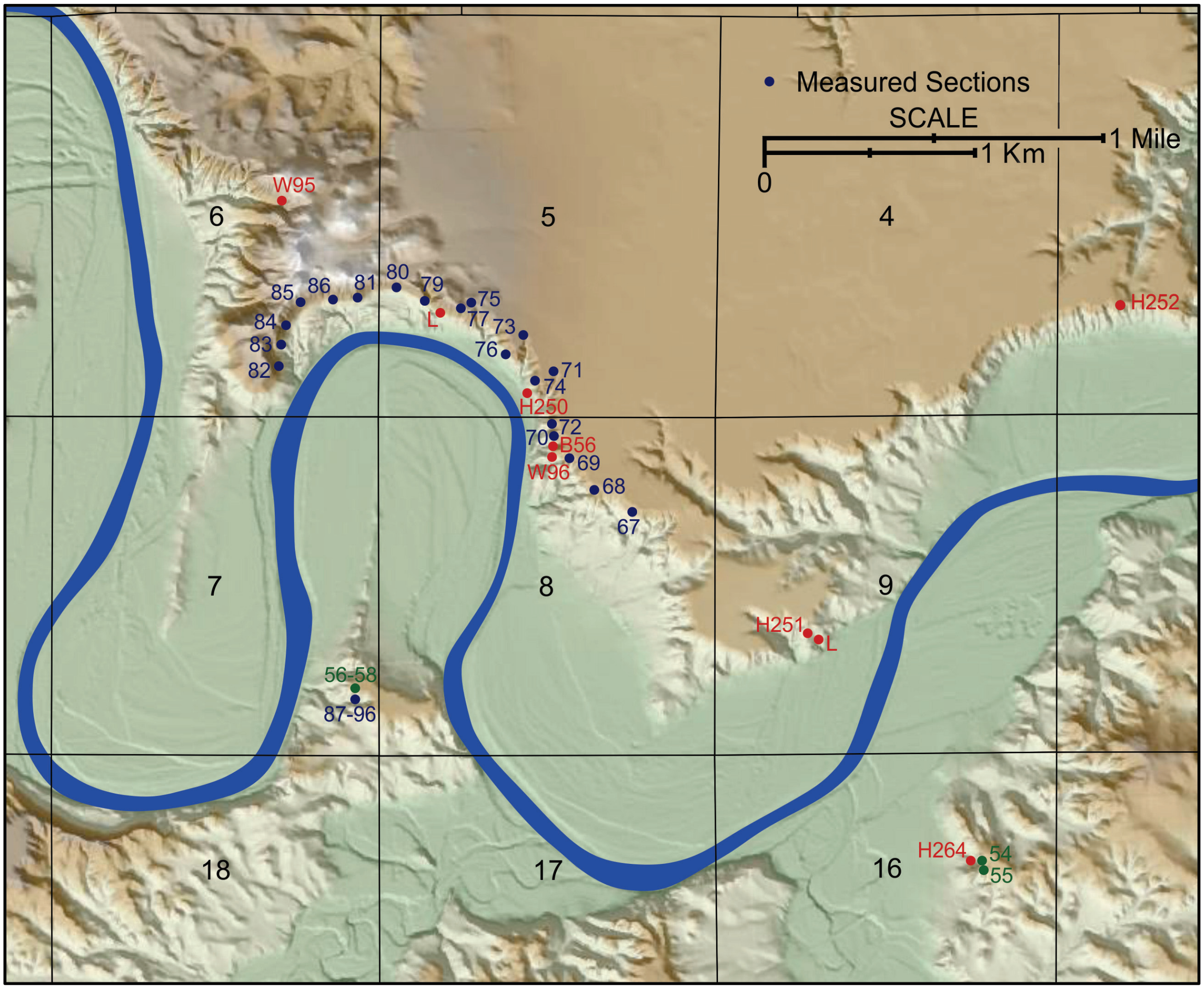


Figure 11. Measured section locations in the Logging Camp Ranch from this study and previous studies. Measured sections 67-86 and 87-96 (this study); W95 and W96 (Warwick, 1982 and Warwick et al., 2004); L (Leonard, 1908); B56 (Belt et al., 2004); H250,H251, H252, and H264 (Hares, 1928); 54 - 58 (Kruger et al., 2017).

River (Hares' sections 250 and 252) (Figure 11). Drilling along the southern edge of the fluvial terrace in the northeast quarter of section 8 and the southwest quarter of section 9 (T136N, R102W) would likely resolve this issue. In the light of the detailed stratigraphic information generated by this report and the presence of a tonstein in the Hanson bed (later discussed in detail) this report is proposing new coal correlations in the study area (Figure 13).

A dozen or more thin lignites were encountered above the Harmon bed in the Tepee Buttes area. While most coals were less than one foot (0.3 m) thick and appear to have limited extent, three were approximately two feet (0.6 m) thick and extended over much of the study area (Figures 10 and 14). An upper coal pair is present between measured sections 75 and 82 with a lateral extent of at least 4,000 feet (1,219 m). The other two-foot (0.6 m) coal is situated 5-10 feet (1.5-3 m) above the Harmon bed and also extends for more than 4,000 feet (1,219 m) (Figure 10).

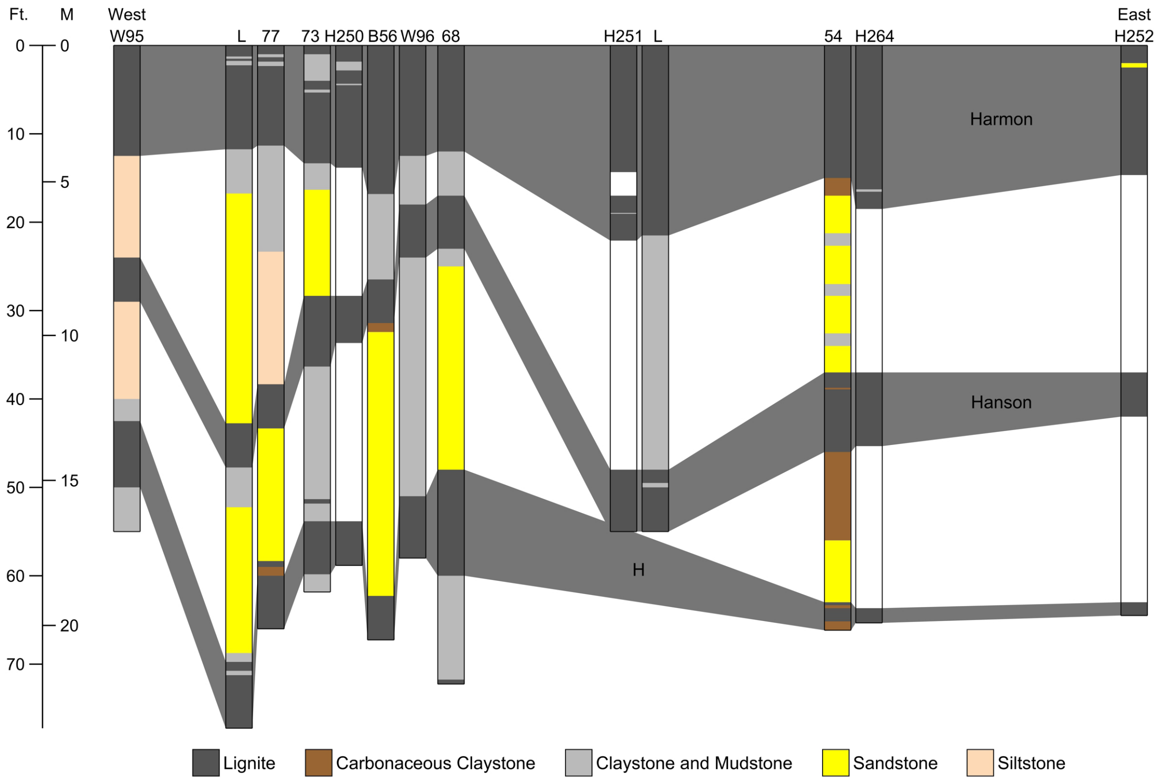


Figure 12. A generalized stratigraphic cross-section across Logging Camp Ranch using the coal correlations of previous workers. See Figure 11 for section affiliations and locations.

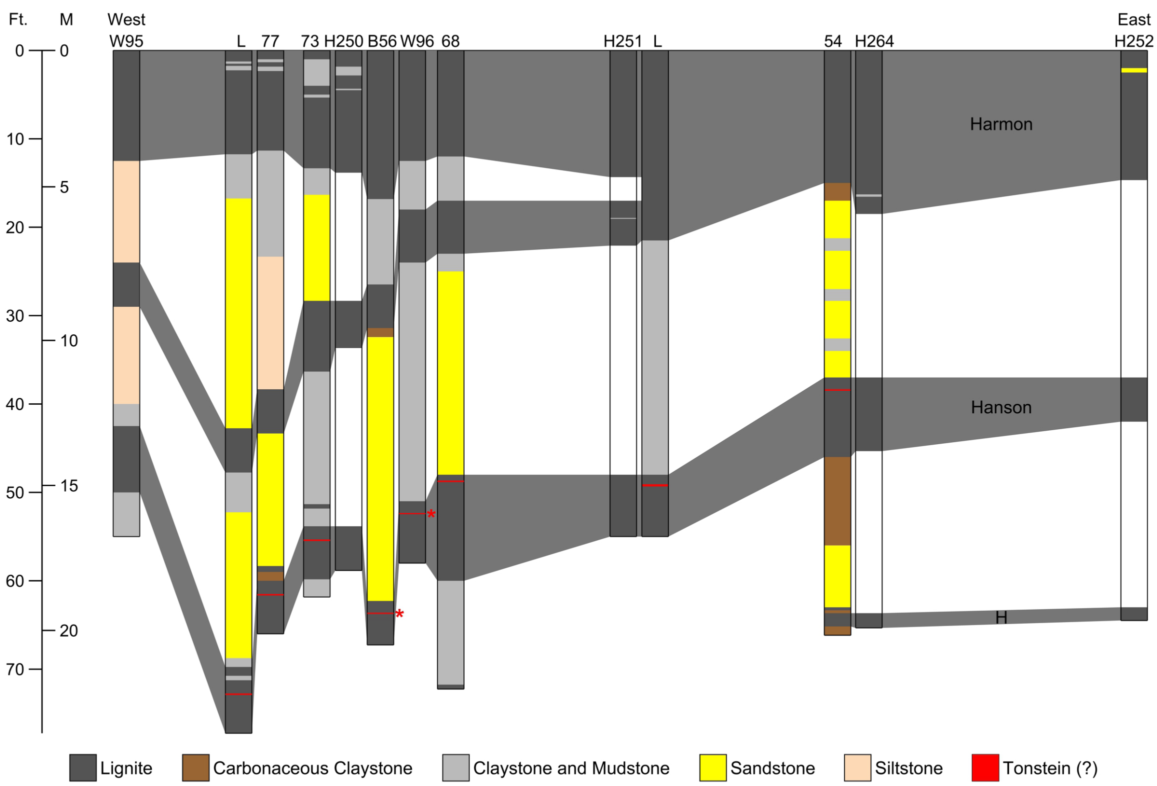


Figure 13. A generalized stratigraphic cross-section across Logging Camp Ranch using the coal correlations of this study. The red asterisk (sections B56 and W96) denotes a confirmed tonstein. See Figure 11 for section affiliations and locations.

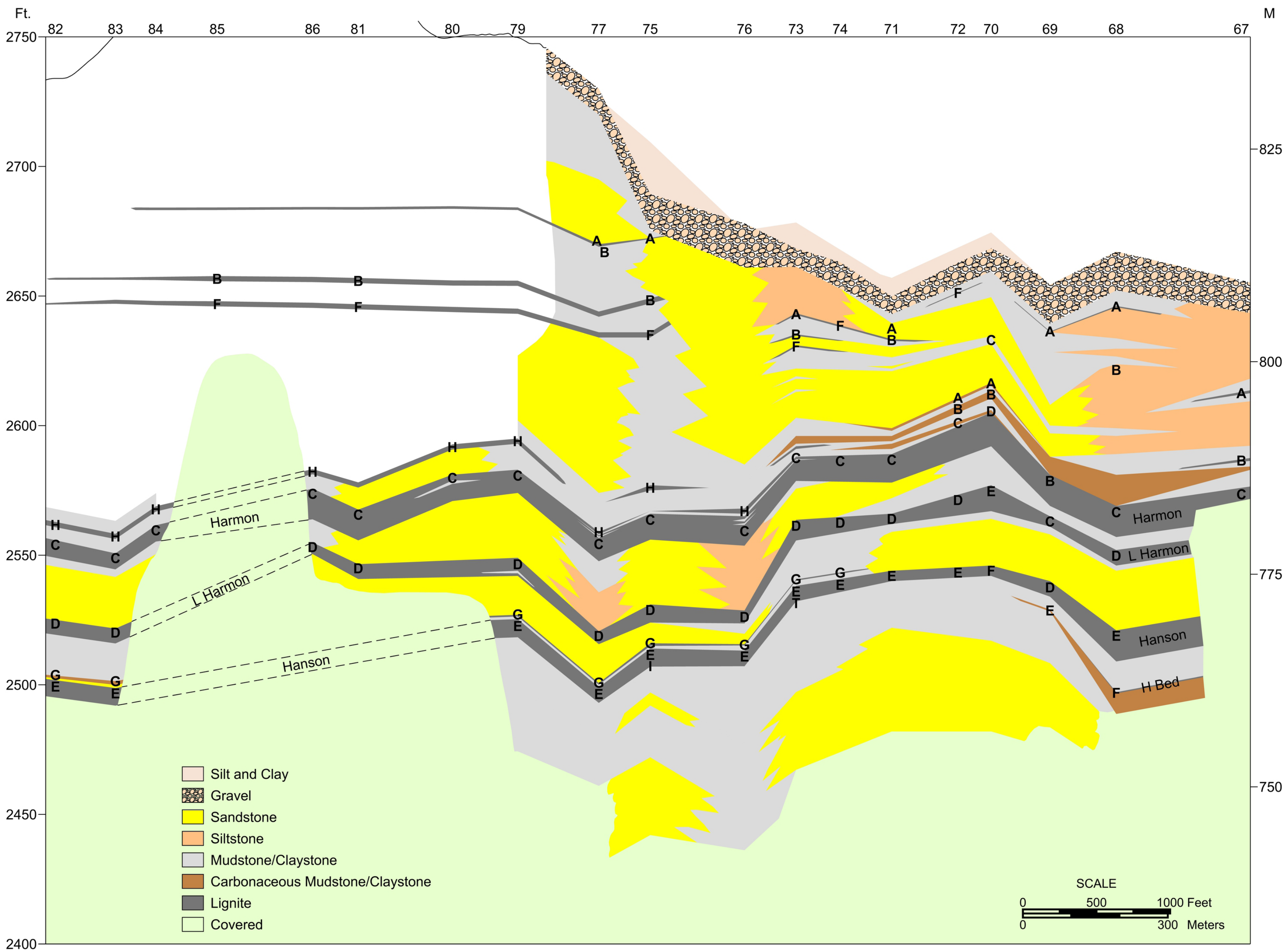


Figure 14. The locations of the rock samples submitted for rare earth analysis for sections 5, 6, and 8.

Table 1. Rare earth concentrations by stratigraphic position.

		Mesured sections below Tepee Buttes									Measured sections below terrace gravel													
		82	**83**	**84**	**85**	**86**	**81**	**78**	**80**	**79**	**77**	**75**	**76**	**73**	**74**	**71**	**72**	**70**	**69**	**68**	**67**	MIN	MAX	**AVG**
Thin upper coals	Highest coals in section							82			265	203		113	180	234	181	152	319	232	158	82	319	**197**
											159					153				137		137	159	**147**
	Upper coal pair				155		139					173		155								139	173	**156**
					132		83					64		171								64	171	**135**
	Coal/carbs above Harmon																178	149			210	149	210	**179**
																	182	187				182	187	**185**
Harmon-Hanson interval	Coal above Harmon	132	120	160		132			89	54	138	110	101									54	160	**107**
	Top of upper Harmon	120	275	96		233	123		76	121	54	90	32	106	130	74	145	108	74	64	101	32	275	**111**
	Top of lower Harmon	152	110			89	119			38	78	33	61	57	129	44	124	59	179	168		33	179	**108**
	Thin coal above Hanson	227	166							109	236	73	162	136	139							73	236	**146**
	Top of Hanson	223	122							155	216	87	144	82	145	54	100	57	38	214		38	223	**106**
	Tonstein													325								325	325	**325**
	Base of Hanson											47										47	47	**47**
	H bed																		171	638		171	638	**405**

Rare Earth Concentrations on the North Side of the River

More than one-third of the project samples north of the river were taken from thin coals and carbonaceous claystones located in the stratigraphic interval below the base of the terrace gravel and above the Harmon bed (Figure 14, Appendix A). Focus was placed on this interval because it was thought that high rare earth concentrations at the top of the Harmon bed in measured sections 56 and 57 (Kruger et al., 2017) could be attributable to leaching from volcanic rocks in the overlying terrace gravel. Only three feet (0.9 m) of mudstone separates the gravel from the underlying Harmon coal in sections 56 and 57 of that study, while in measured sections 67-77 of this study there is 50-160 feet (15.2-48.8 m) of rock between the base of the terrace gravel and the top of the Harmon bed (Figure 14). For that reason, an emphasis was placed on sampling carbonaceous beds as close to the base of the terrace gravel as possible. Many of these thin coals or carbonaceous claystones are tens of feet (>3 m) below the gravel, but those represented by samples 68A (6 ft, 1.8 m), 69A (3 ft, 0.9 m), 71A (3 ft, 0.9 m), 72F (5 ft, 1.5 m), and 75A (3 ft, 0.9 m) are all within six feet (1.8 m) of the gravel. Although samples 73A and 74F (thin carbonaceous claystones) are 10-20 feet (3-6.1 m) below the base of the gravel, they are overlain by sandstone and siltstone in direct contact with the gravel.

In general, there is a decrease in rare earth concentrations with depth below the gravel (Figures 15 and 16, Tables 1 and 2). However, only one sample (69A) in close proximity to the gravels, a four-inch (10 cm) thick carbonaceous claystone, had a rare earth whole rock analysis above 300 ppm (319 ppm). The variable quality between the thin lignites and the carbonaceous claystones may mask a contribution from the gravel. Conversely, the lack of high rare earth concentrations in proximity to the gravel calls into question the contribution of gravel leachate to the high rare earth concentrations in sections 56 - 58 (Kruger et al., 2017) or may reflect the nonhomogeneous nature of the gravel with respect to leachable rare earth elements. Highly-localized groundwater patterns within the Bullion Creek Formation may also play a role in the observed outcrop-scale variability in rare earth concentrations. In addition, B and F samples do not demonstrate a discernable difference in rare earth concentrations for that portion of the upper coal pair below terrace gravel (section 75) compared to that portion which is not (sections 81 and 85) (Figures 15 and 16, Table 1). The laterally extensive, two-foot (0.6 m)-thick lignite situated 5-10 feet (1.5-3 m) above the Harmon bed (samples 75H, 79H, 80H, 82H, 83H, 84H, and 86H) contains rare earth concentrations of 54-160 ppm with an average concentration of 114 ppm.

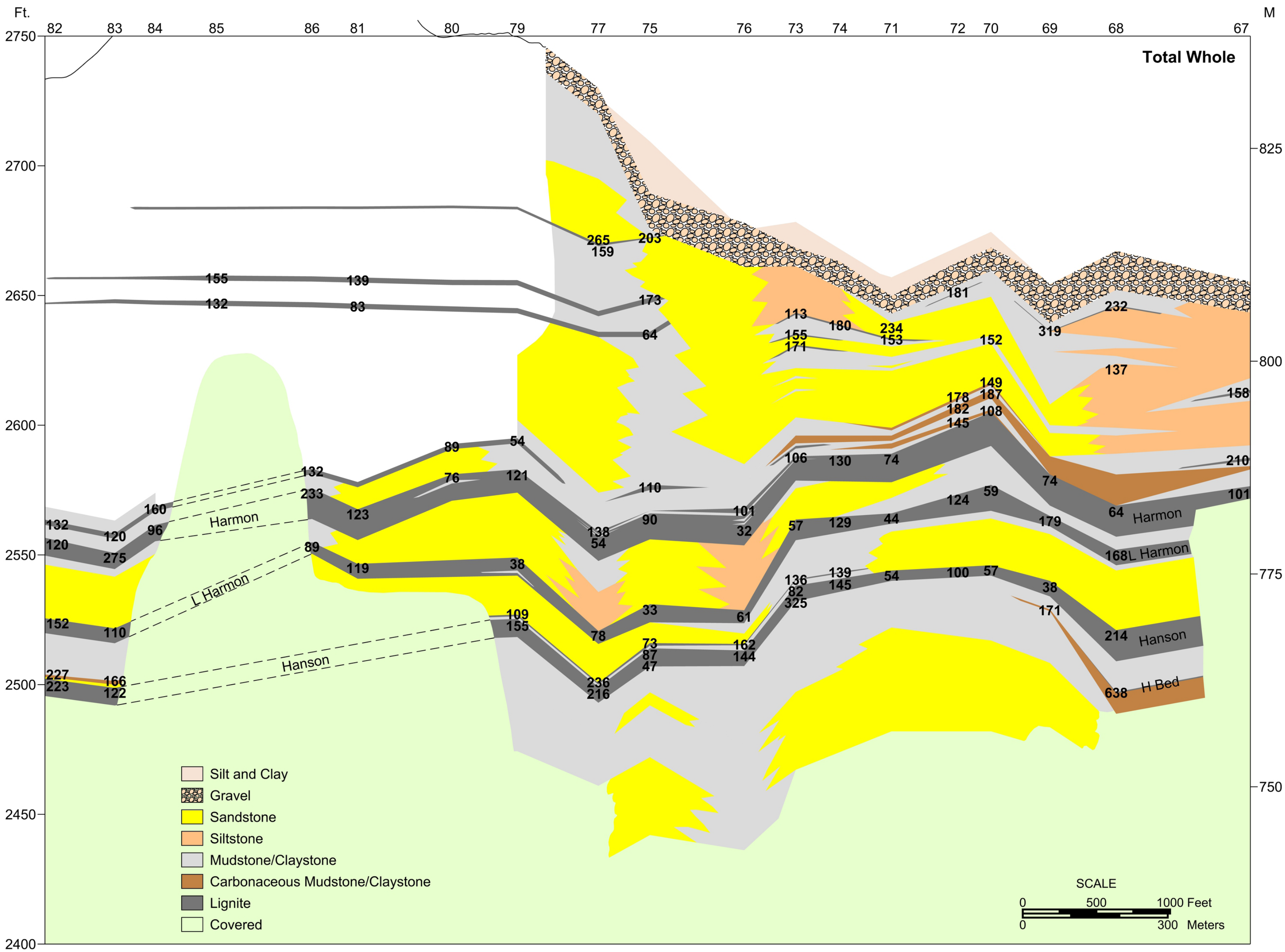


Figure 15. Rare earth element whole rock analysis cross section for sections 5, 6, and 8.

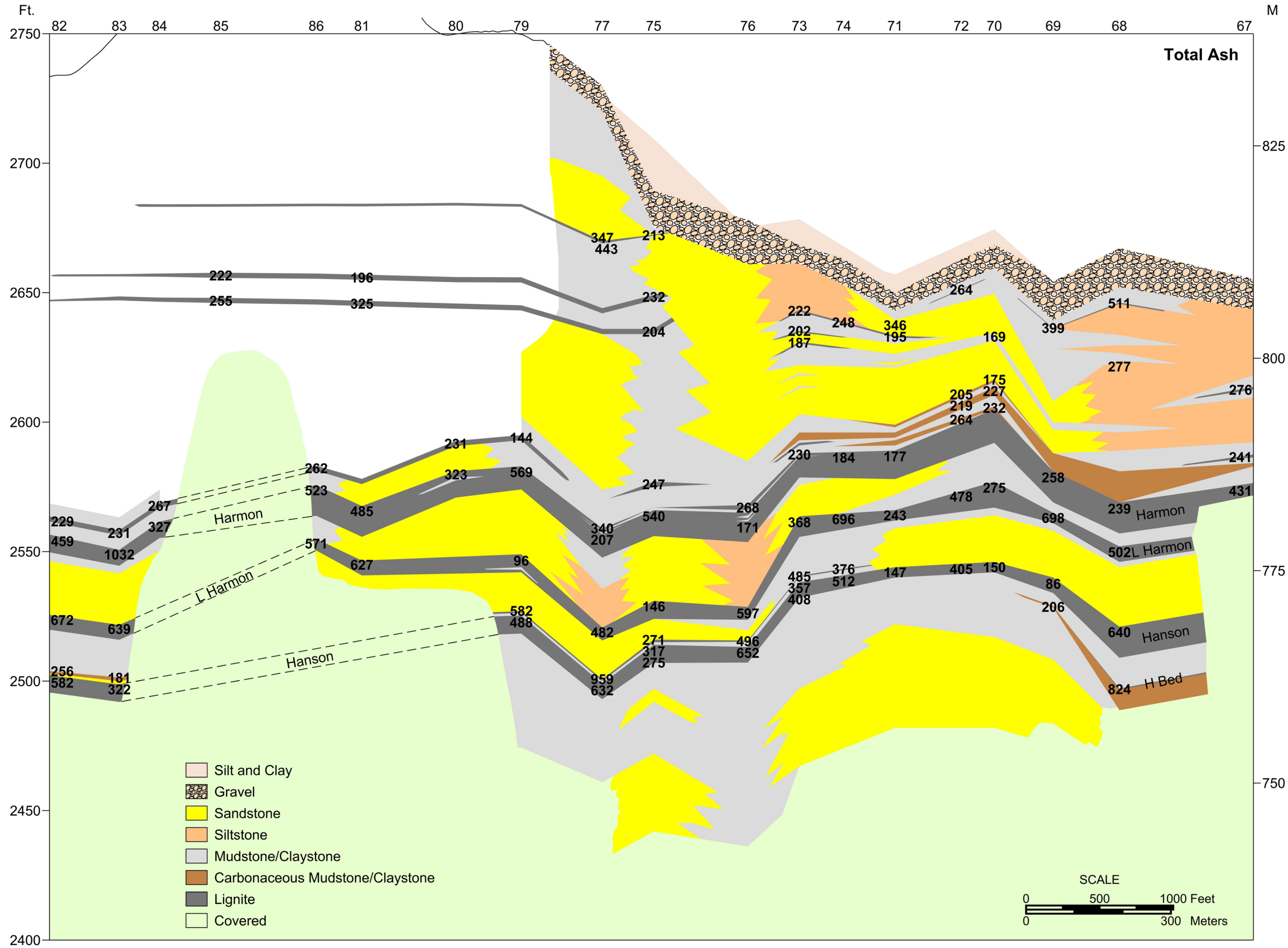


Figure 16. Rare earth element analysis cross section on a total ash basis for sections 5, 6, and 8.

Table 2. Rare earth concentrations of upper and lower coal groups in relation to terrace gravels.

	Below Tepee Buttes					Below terrace gravels				
	Number of samples	% Ash	ΣREE (ppm) MIN	MAX	AVG	Number of samples	% Ash	ΣREE (ppm) MIN	MAX	AVG
Thin upper coals	5	50%	82	155	**118**	22	68%	64	319	**180**
Harmon-Hanson interval	24	32%	38	275	**135**	43	32%	32	638	**124**
Total	29	34%	38	275	**132**	65	42%	32	638	**143**

Harmon Bed

Eighteen lignite samples were taken from the top three inches (7.6 cm) of the Harmon bed on the north side of the river. The rare earth concentrations ranged from 32 to 275 ppm with an average value of 111 ppm (Figure 15, Table 1) Sample 83C was the high with 275 ppm on a whole rock basis and 1,032 ppm rare earths on an ash basis (Figures 15 and 16, Appendices A and B). The coal quality at the top of the Harmon bed was fairly consistent throughout this area.

Lower Harmon Bed

Fifteen coal samples were taken from the top three inches (7.6 cm) of the lower Harmon bed, identified by previous workers in this area (Leonard, 1908; Hares, 1928; Warwick, 1982; Warwick and Luck, 1995; Belt et al., 2004; and Warwick et al., 2004) as the Hanson bed. Rare earth concentrations ranged from 33 to 179 ppm with an average of 108 ppm (Figure 15, Table 1). Sample 69C had the highest concentrations based on ash analysis (698 ppm) (Figure 16).

Hanson Bed

Thirteen coal samples were taken from the top three inches (7.6 cm) of the Hanson bed, identified by previous workers in this area (Leonard, 1908; Warwick, 1982; Warwick and Luck, 1995; Belt et al., 2004; and Warwick et al., 2004) as the H bed. Rare earth concentrations ranged from 38 to 223 ppm with an average of 106 ppm (Figure 15, Table 1). Sample 76E had the highest concentrations based on ash analysis (652 ppm) (Figure 16).

A thin lignite 1-2 feet (0.3-0.6m) above the Hanson bed contained a range of rare earth concentrations from 73-236 ppm with an average whole rock analysis of 146 ppm. The highest rare earth analysis on an ash basis was 959 ppm in sample 77G (Figure 16).

H Bed

Only two samples were obtained from the H bed north of the river (samples 68F and 69E). These two coal samples were taken from the top three inches (7.6 cm) of the H bed. As previously noted, the lack of outcrops at the crucial junction where the Harmon bed splits in this area resulted in previous workers miscorrelating the Hanson and H beds in the area between measured sections 67 and 82 of this study (Figures 10-13). Sample 68F had a rare earth concentration of 638 ppm, and an ash-based concentration of 824 ppm (Figures 14-17).

Rare Earth Concentrations in Section 16

Two additional samples were taken from the H bed at the section 16 (T132N, R102W) locality where Kruger and others (2017) first reported high rare earth concentrations in this thin coal. These samples were obtained approximately 63 feet (19.2 m) equal distance from Kruger and

Figure 17. The H bed at sample site 68F, the site of the second highest rare earth concentration in this study (638 ppm).

others (2017) two sampling sites (Figure 18). The first sample (97a) was taken from the top three inches (7.6 cm) of the H bed and had a rare earth element concentration of 1,026 ppm (1,718 ppm on an ash basis). The second sample (97b) was collected 10-12 inches (25.4 -30.5 cm) below the top of the coal and contains a rare earth element concentration of 539 ppm (1,939 ppm on an ash basis) (Figure 18). Seven samples from the H bed on Logging Camp Ranch contain an average rare earth concentration of 300 ppm or higher.

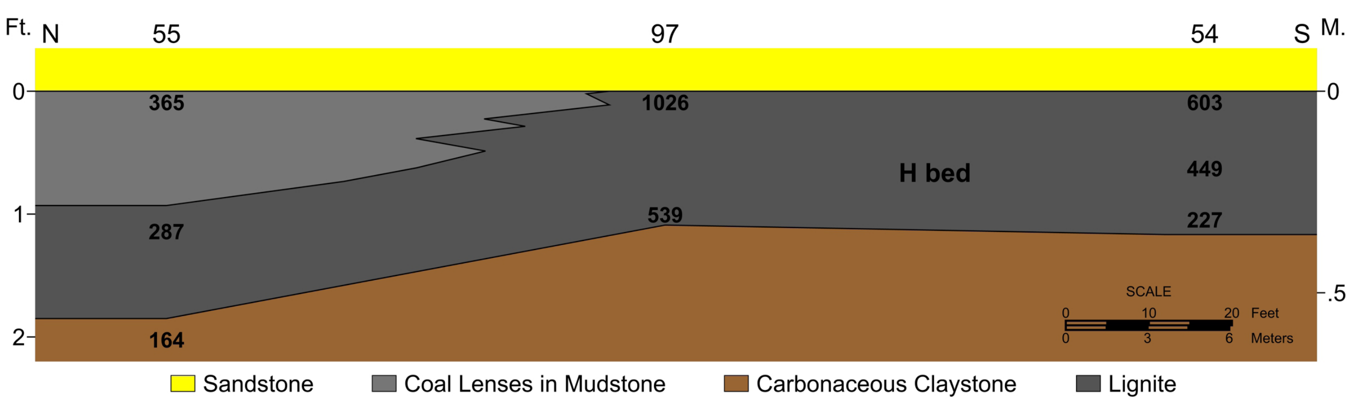


Figure 18.

Rare Earth Concentrations in Section 7

Kruger and others (2017) reported high rare earth element concentrations in coals beneath terrace gravels in measured sections 56-58 (section 7, T136N, R102W). At that locality, the Harmon bed is only a few feet (<1m) below gravel and rare earth concentrations for four samples from the top of the Harmon were 493, 555, 295, and 350 ppm. Measured sections 56 and 57 are spaced 204 feet (62.2m) and sections 57 and 58 are 144 feet (43.9 m) apart (Kruger et al., 2017). Seventeen additional samples were collected from the tops of coals exposed in this ravine at an average spacing of 53 feet (16.2m) to enable lateral variations to be determined at a much finer scale (Figure 4). The vast majority of samples (14) were collected from the top of the Harmon bed. Rare earth element concentrations in the Harmon samples ranged from 132 to 439 ppm (Figure 19). Rare earth concentrations in 18 samples at the top of the Harmon bed at this locality, including those samples reported by Kruger and others (2017), average 314 ppm on a whole coal basis and 914 ppm on an ash basis.

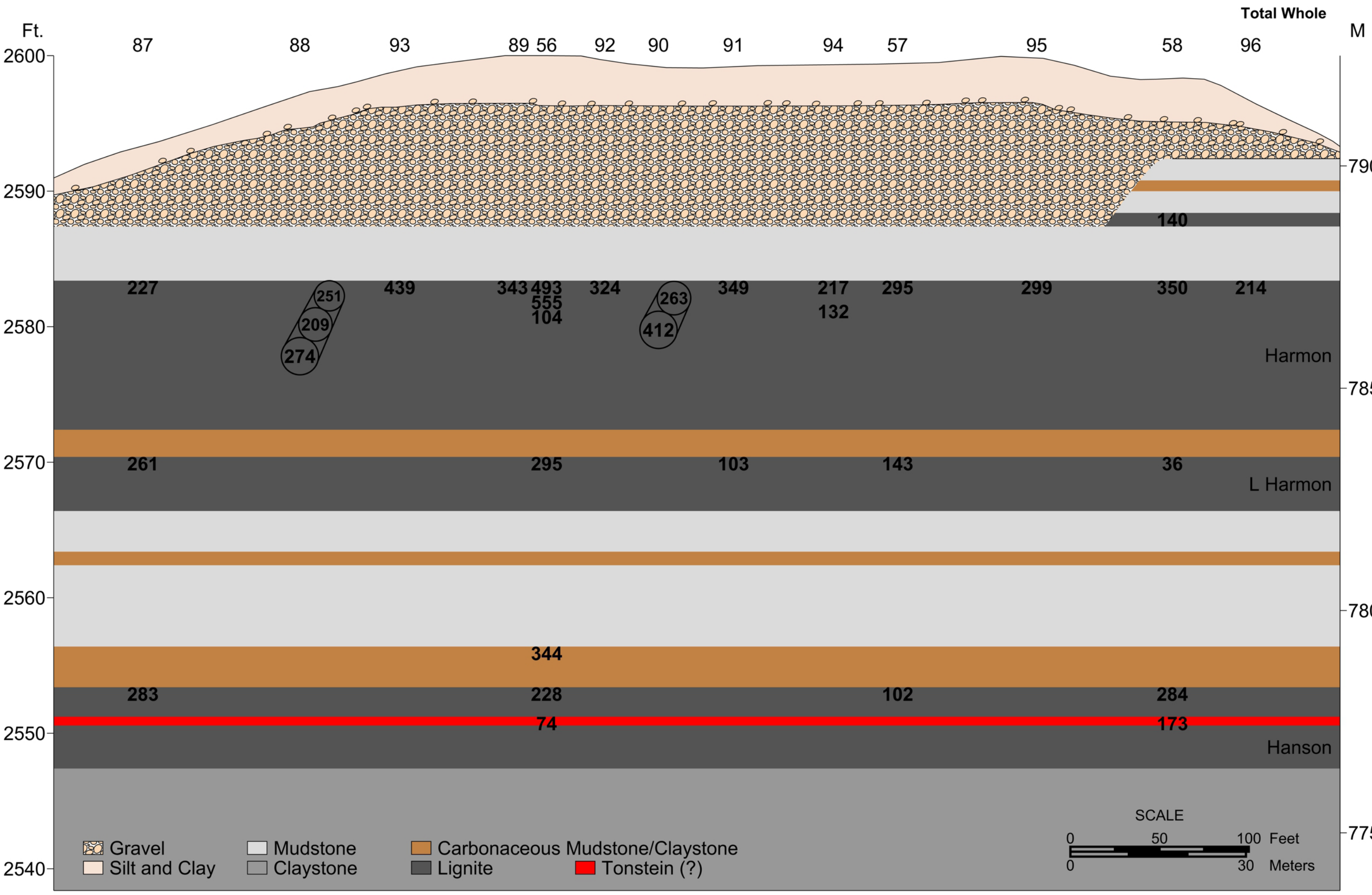


Figure 19. Rare earth element whole rock analysis cross section for Section 7. To gauge the effects of surface weathering at the outcrop face, samples were taken at various depths into the outcrop at the top of the Harmon bed in measured sections 88 and 90. Sample 88A was taken 1-2 feet (0.3-0.6 m) into the coal, sample 88B was taken 2-3 feet (0.6-.0.9 m), sample 88C was taken at 3-4 feet (0.9-1.2 m), 90A at 1-2 feet (0.3-0.6 m), and 90C was taken at 3-4 feet (0.9-1.2 m) into the coal.

Figure 20. Potential tonstein (arrow) in the upper part of the Hanson bed at measured section no. 73 (sample 73T).

Figure 21. Potential tonstein (arrow) in the upper Hanson bed at Kruger and others (2017) measured section no. 54 and Hares (1928) measured section no. 264.

Tonsteins

Tonsteins are thin, widespread, kaolinite-rich claystones, with sharp bed contacts, that formed from the alteration of volcanic ash deposits in a nonmarine environment (Bohor and Triplehorn, 1993). It is often difficult to distinguish whether a thin claystone in a Fort Union lignite is a tonstein or simply a thin, clay parting (Figures 20 and 21). Fortunately, tonsteins typically have a greasy feel when rubbed between the thumb and forefinger due to the presence of kaolinite. In addition, Fort Union tonsteins often have a slight pinkish cast or hue. As a field test, Bohor and Triplehorn (1993) suggested chewing a piece of potential tonstein; noting that a tonstein should feel smooth due to the loss of quartz through alteration while clay partings should feel gritty. Warwick and others (2004) collected 23 potential tonsteins from lignites in the Fort Union Group. However, as an example of the potential difficulty of

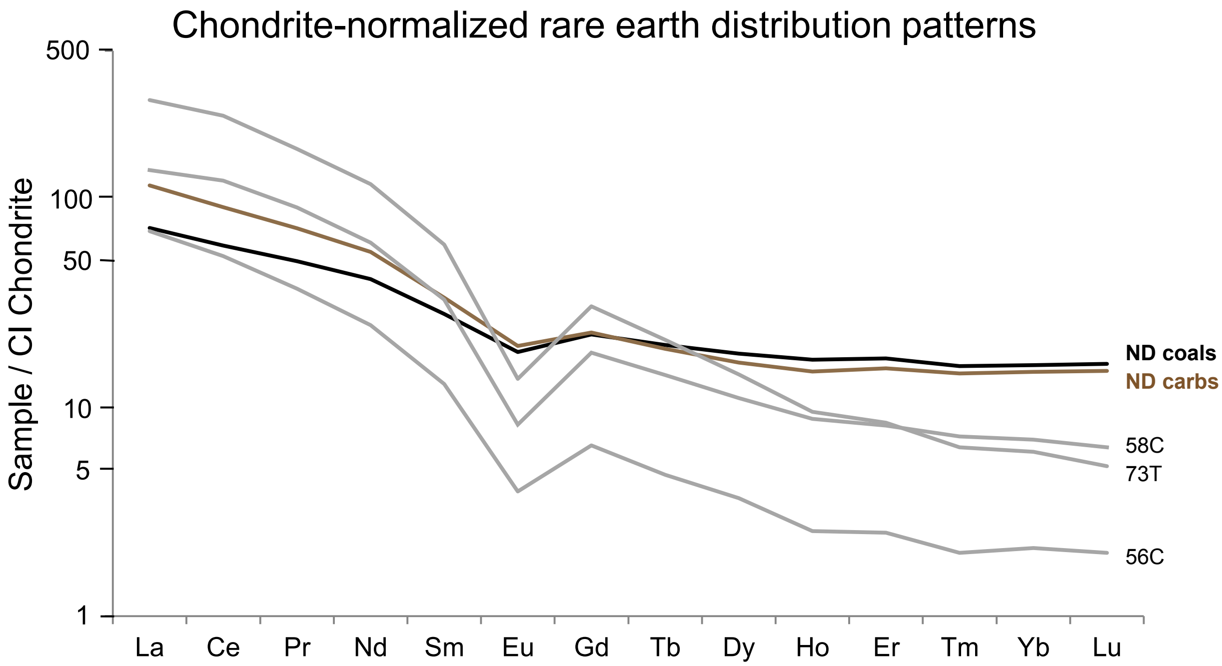


Figure 22. A distinct negative europium anomaly in three samples of a thin claystone within the Hanson coal bed at Logging Camp Ranch supports the interpretation of this bed as a volcanic ash-derived tonstein (Bohor and Triplehorn, 1993). Coals and detrital mudstones and claystones of the Fort Union Group show only small negative europium anomalies. Rare earth concentrations are normalized for carbonaceous chondrites based on the values of McDonough and Sun (1995). Samples 56C, 58C, and averages for coal and carbonaceous mudstone in western North Dakota from Kruger and others (2017).

identifying tonsteins in the field, many of these samples were later determined to either not be tonsteins or lacked sufficient quantities of sanidine or zircon crystals to enable radiometric dating.

Tonsteins can be confirmed in the laboratory by the presence of volcanogenic mineral forms such as high temperature quartz, biotite, sanidine, and zircon crystals (Bohor and Triplehorn, 1993; Dai et al., 2017). Bohor and Triplehorn (1993) noted that tonsteins have rare earth element "chondrite-normalized patterns" similar to those patterns seen in rhyolitic ashes which includes a large negative europium anomaly (Figure 22). Forsman (1985) determined that the volcanic glass within the Sentinel Butte bentonite/ash was rhyolitic in composition and believes (N. Forsman, personal communication, February 14, 2018) all volcanic ashes, tuffs, and tonsteins within the Fort Union Group in North Dakota are likely rhyolitic (70-72% silica). This is in agreement with Bohor and Triplehorn (1993) who stated that most widespread tuffs are sourced from rhyolitic magmas.

One potential tonstein was sampled during this project. The sample (73T) was collected from a three-inch (7.6 cm) claystone located 18 inches (45.7 cm) below the top of the Hanson bed in measured section no. 73 (Figures 14 and 20). This thin, pinkish/white claystone can be traced through much of the study area and ranges in thickness from two to six inches (5.1-15.2 cm). In all likelihood, this is the "H bed" tonstein reported by previous workers in this area (Warwick et al., 1995, Belt et al., 2004; and Warwick et al., 2004). This tonstein appears to correlate with a probable tonstein located in the upper portion of the Hanson bed in Hares'(1928) measured section 264, Kruger and others (2017) section no. 54 (Figure 20), and Leonard's (1908) measured section 136-102-9, reinforcing the coal correlations made in this report (Figure 13).

Tonstein sample 73T was compared to two samples from the Hanson bed tonstein collected one mile to the southwest by Kruger and others (2017), samples 56C and 58C. The total rare earth concentrations of these three samples ranges from 74 – 325 ppm, but the relative percentages of many of the individual elements are very similar. This is especially true for europium. As predicted by Bohor and Triplehorn (1993) for rhyolitic tonsteins, of the 446 samples submitted for rare earth analysis by both Kruger and others (2017) and this study, these three samples contained the lowest percentage of europium in relation to total lanthanides (Figure 22).

Conclusions

The Harmon bed appears to split within the Logging Camp Ranch into an upper and a lower bed. Detailed stratigraphic study of this area was needed in order to recognize this coal split which is why previous workers were unable to do so. In addition to closely spaced measured sections, tonstein correlation was a valuable tool in verifying the coal stratigraphy in this area.

Samples from this study as well as those from Kruger and others (2017) were collected one foot (0.6 m) into the outcrop face to minimize the effects of surface weathering on rare earth element concentrations. To further evaluate the potential effects of surface weathering, samples 88A-88C, 90A, and 90C were excavated 1-4 feet (0.6-1.2m) further into the coal face (Figure 19). At both localities, the highest rare earth concentrations were contained in the sample closest to the outcrop face suggesting that surface leaching is not a factor at this location. Additional sampling of this type will be employed at several future localities to test the results from this rather modest number of samples.

Although precautions were taken to obtain fresh rock samples, surface leaching of rare earths could be a factor in both this study and the Kruger and others (2017) study. Coring these same rocks one half mile (0.8 km) north of measured sections 67-79, in the middle of the fluvial terrace, and analyzing those coals for rare earths may be the only way to conclusively determine whether surface leaching along the edges of this terrace have resulted in the relative absence of the high concentrations found in section 7. On the other hand, if this relative absence of high rare earth concentrations can be attributed to surface leaching, concentrations should not have been elevated in measured sections 56-58 and 87-96, unless the headword erosion of the ravine at that locality is younger than the erosional processes exposing the cliff face along measured sections 67-86.

This project was initiated to test the lithologic and stratigraphic hypotheses addressing high rare earth concentrations generated by Kruger and others (2017), who identified trends in elevated rare earth concentrations in (1) the upper portions of coal beds, (2) coals beneath sandstone and gravels, and (3) the Harmon, Hanson, and H bed lignites at Logging Camp Ranch, which returned four of the five highest samples analyzed in their study. This project was, in fact, a second phase of that original work. The clean, steep cliffs on the north side of the Little Missouri River in the study area offered the perfect opportunity to check for lateral variations in the rare earth concentrations at the tops of three-thick-persistent coal beds (Harmon, lower Harmon, and Hanson) and to determine the contributions the overlying rocks had on those concentrations.

Table 3. Rare earth concentrations across the top of the three major coal beds north of the river.

		Overlain by claystone/mudstone				Overlain by siltstone/sandstone			
	% Ash	Number of samples	ΣREE (ppm) MIN	MAX	AVG	Number of samples	ΣREE (ppm) MIN	MAX	AVG
Top of Harmon bed	30%	16	32	275	**114**	2	76	123	**100**
Top of lower Harmon bed	20%	8	44	179	**106**	7	33	152	**84**
Top of Hanson bed	31%	6	82	216	**138**	7	38	223	**115**
Total		30	32	275	**117**	16	33	123	**100**

A total of 46 samples were taken from the tops of the Harmon, lower Harmon, and Hanson beds in this study on the north side fo the river. Ten percent of the Harmon samples, 47% of the lower Harmon samples, and 54% of the Hanson samples were obtained from localities where those coals were overlain by sandstone or siltstone. A comparison of the rare earth concentrations of the 16 coal samples overlain by sandstone to the 30 samples overlain by mudstone and claystone does not show enrichment for those coals beneath sandstone. Instead, where overlain by claystone and mudstone, these coal tops have an average of 117 ppm as compared to 100 ppm for coals overlain by sandstone (Table 3). The apparent lack of impact on rare earth concentrations from both sandstones and gravel suggests that leaching of rare earths from overlying rocks (as gross lithologies, eg., sandstone vs. mudstone) was not a factor at this site and the marginally increased average rare earth concentrations of coals beneath sandstone identified by Kruger and others (2017) is likely not significant. This would explain their inability to generate an exploration model as noted in their report.

A comparison of rare earth concentrations of thin coals in close proximity to the terrace gravel to those beyond 25 feet (7.6 m), but above the Harmon bed, failed to demonstrate consistent enrichment of the coals in closest proximity to the gravel (Figure 15). It may be that even the closest coals are too far below the gravel as compared to sections 56 and 57 in Kruger and others (2017). The measured sections 67-79 and 56-58 localities are both capped by terrace gravels. However, in sections 67-79, the top of the Harmon bed is up to 160 feet (48.8m) further beneath the base of the gravel than at sections 56-58. This alone could explain the lack of high rare earth concentrations in the Harmon bed at this site. Many of the samples from thin coals above the Harmon bed were collected in close proximity to the gravel and yet did not exhibit high rare earth concentrations. This cannot be attributed to a decrease in coal quality because Kruger and others (2017) also found that thin, powdery lignites tended to contain rare earths at higher concentrations than the thicker, harder lignites.

Terraces

Biek and Gonzalez (2001) recognized four fluvial terraces 160 feet (49m), 220 feet (67m), 240 feet (73m), and 260 feet (79m) above the modern drainage of the Little Missouri River, 25 miles to the north in the South Unit of the Theodore Roosevelt National Park. A profile through a portion of the Logging Camp Ranch demonstrates there are at least three terraces (T1-T3), with T1 being the oldest or highest terrace preserved in this immediate area and T3 being the youngest (Figure 23). Sections 67-77 were measured in an area where the rocks underlie T2 gravels while sections 56-58 and 87-96 were measured in an area where the rocks are overlain by the T3 terrace. Coals

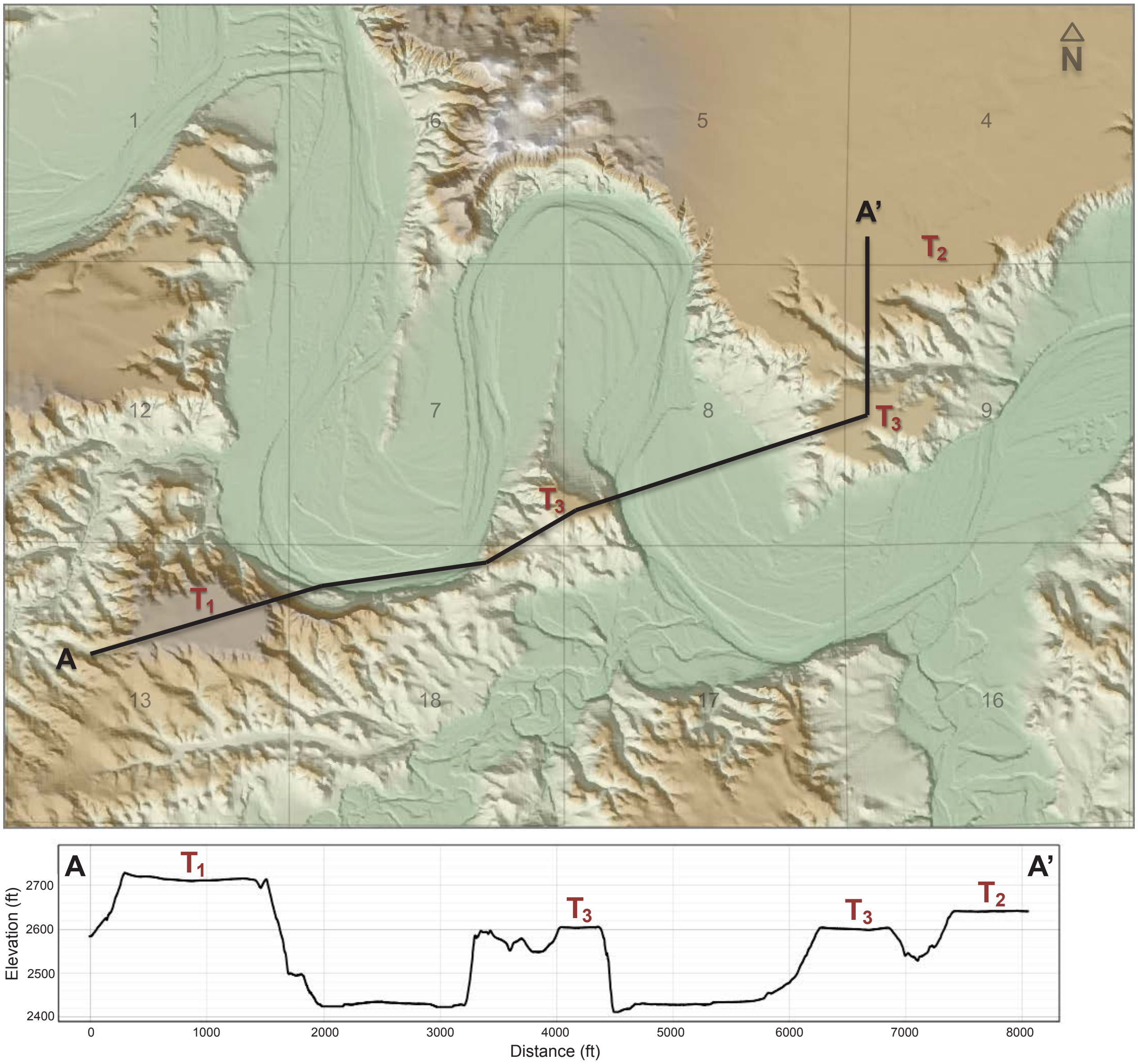


Figure 23. LiDAR image of the Logging Camp Ranch area. Elevation profile across the Little Missouri River Valley showing three distinct terrace levels.

below the T3 terrace generally contain much higher concentrations of rare earth elements than those beneath the T2 terrace suggesting the younger gravels may contain more leachable rare earth elements in comparison with those in the T2 terrace. That is, if leaching from gravel is a contributing factor at these localities (Figure 23).

Given the apparent lack of connection between rare earth concentrations at the tops of Fort Union lignites and the gross lithology of the overlying strata, the next logical step is look at variables that are not observable in the field. While documented tonsteins have been found within the Fort Union Group in North Dakota (e.g., Warwick et al., 1995; Belt et al., 2004; and Warwick et al., 2004), they appear to be relatively rare. Along those lines, high rare earth concentrations in coals may largely be the result of volcanic ash that was mixed with the peat in amounts less than it would take to eventually generate a tonstein (Dai et al., 2017). The propensity for high rare earth concentrations to occur at the top of coals, rather than randomly throughout the bed, might argue both for and against this theory, depending upon how common it is in the Fort Union rock record. As noted by Dai and others (2017), influxes of volcanic ash can choke out vegetation and terminate peat accumulation. Kruger and others (2017) evaluated the reliability of an exploration model where elevated rare earth element concentrations at the tops of lignites overlain by sandstone had been leached from relatively long distances by groundwater preferentially flowing through these channel sandstones and precipitating along the first organic-rich horizon that was encountered. That this model was only applicable 24% of the time had them questioning its validity and looking for more localized post-depositional phenomena or factors coincident with deposition. The findings in this study bring into further question an exploration model based primarily on the gross lithologies overlying coals.

Based on a detailed review of the USGS COALQUAL database, Lin and others (2018) considered a total rare earth concentration of 653 ppm (from a Mississippi lignite) to be the highest quantitatively-measured whole coal analysis of 5,378 samples from across the United States. H bed sample 97a of this study, with a whole-coal total rare earth concentration of 1,026 ppm, appears to be the highest concentration yet reported for a U.S. coal.

It is anticipated that further studies will continue to push these values higher as the search continues for consistently high rare earth concentrations over an extended area. Already a number of sites have been identified within the Logging Camp Ranch area, as well as other parts of western North Dakota, where coal samples will be collected in order to determine the impact concurrent deposition of peat and volcanic ash had on rare earth concentrations in North Dakota lignites.

References

Belt, E.S., Hartman, J.H., Diemer, J.A., Kroeger, T.J., Tibert, N.E., and Curran, H.A., 2004, Unconformities and age relationships, Tongue River and older members of the Fort Union Formation (Paleocene), western Williston Basin, U.S.A.: Rocky Mountain Geology, v. 39, no. 2, p. 113-140.

Biek, R. F., and Gonzalez, M. A., 2001, The geology of Theodore Roosevelt National Park, Billings and McKenzie counties, North Dakota: North Dakota Geological Survey Miscellaneous Series No. 86, 74 p.

Bohor, B.F. and Triplehorn, D.M., 1993, Tonsteins: altered volcanic-ash layers in coal bearing sequences: Geological Society of America Special Paper, no. 285, 44 pp.

Brant, R.A., 1953, Lignite Resources of North Dakota: U.S. Geological Survey Circular, no. 226, 78 pp.

Dai, S., Ward, C.R., Graham, I.T., French, D., Hower, J.C., Zhao, L., and Wang, X., 2017, Altered volcanic ashes in coal and coal-bearing sequences: a review of their nature and significance: Earth Science Reviews, 175, p. 44-74.

Forsman, N.F., 1985, Petrology of the Sentinel Butte Formation (Paleocene) in North Dakota: PhD dissertation, University of North Dakota, 222 p.

Hares, C.J., 1928, Geology and lignite resources of the Marmarth Field, southwestern North Dakota: United States Geological Survey Bulletin, no. 775, 110 p.

Kopseng, L.H., 1976, Logging Camp Ranch: Slope County Saga, Pioneer Print, Bowman, p. 1101-1104.

Kruger, N.W., Moxness, L.D., and Murphy, E.C., 2017, Rare earth element concentrations in Fort Union and Hell Creek strata in western North Dakota: North Dakota Geological Survey Report of Investigation, no. 117, 104 p.

Leonard, A.G., 1908, The geology of southwestern North Dakota with special reference to coal: North Dakota Geological Survey Fifth Biennial Report, p. 27-115.

Leonard, A.G. and Smith, C.D., 1907, The Sentinel Butte lignite field, North Dakota and Montana: U.S. Geological Survey Bulletin 341, p. 15-35.

Lin, R., Soong, Y., and Granite, E.J., 2018, Evaluation of trace elements in U.S. coals using the USGS COALQUAL database version 3.0. Part I: Rare earth elements and yttrium (REY): International Journal of Coal Geology, 192, p. 1-13.

McDonough, W.F. and Sun, S.S., 1995, The Composition of the Earth: Chemical Geology, 120, p. 223-253.

Murphy, E.C., 2002, The Hanson (Not Hansen) Lignite Bed: NDGS Newsletter, North Dakota Geological Survey, vol. 29, no. 2, p. 1-2.

Murphy, E.C., 2006, The lignite reserves of North Dakota: North Dakota Geological Survey Geologic Investigations, no. 104, 141 p.

Murphy, E.C., 2012, Depth to the Harmon Bed: North Dakota Geological Survey Geologic Investigations no. 159, poster.

Murphy, E.C., Hoganson, J.W., and Forsman, N.F., 1993, The Chadron, Brule, and Arikaree Formations in North Dakota – The Buttes of Southwestern North Dakota: North Dakota Geological Survey Report of Investigation, no. 96, 144 p.

Murphy, E.C., Kruger, N.W., and Goven, G.E., 1999, The major coals in Bowman, Slope, Adams, and Hettinger counties, North Dakota: North Dakota Geological Survey Open File Report 99-1, 56 p.

Murphy, E.C., Kruger, N.W., and Goven, G.E., 2000, The major coals in Billings, Golden Valley, and Stark counties, North Dakota: North Dakota Geological Survey Open File Report 00-1, 42 p.

Murphy, E.C., Kruger, N.W., Vandal, Q.L., Goven, G.E., and Tudor, E.A., 2002, The Harmon Lignite Bed in Western North Dakota: North Dakota Geological Survey Miscellaneous Map, no. 35.

Roberts, H., 1976, Huidekoper Ranches Compared: Slope County Saga, Pioneer Print, Bowman, pp. 1099-1101.

Warwick, P.D., 1982, The geology of some lignite-bearing fluvial deposits (Paleocene), south-western North Dakota: M.S. thesis, North Carolina State University, 116 p.

Warwick, P.D. and Luck, K.R., 1995, Stratigraphic sections of the lignite-bearing Tongue River Member, Fort Union Formation (Paleocene), southwestern North Dakota: United States Geological Survey Open File Report 95-676, 38 p.

Warwick, P.D., Flores, R.M., Murphy, E.C., and Obradovich, J.D., 1995, Parasequences in the Paleocene Ludlow and Cannonball Members of the Fort Union Formation, Williston Basin, North Dakota: Geological Society of America Abstracts with Programs, v. 27, no. 4, p. 60.

Warwick, P.D., Flores, R.M., Nichols, D.J., and Murphy, E.C., 2004, Chronostratigraphic and depositional sequences of the Fort Union Formation (Paleocene), Williston Basin, North Dakota, South Dakota, and Montana, in J.C. Pashin and R.A. Gastaldo, eds., Sequence stratigraphy, paleoclimate, and tectonics of coal-bearing strata: AAPG Studies in Geology 51, p. 121-145.

APPENDICIES

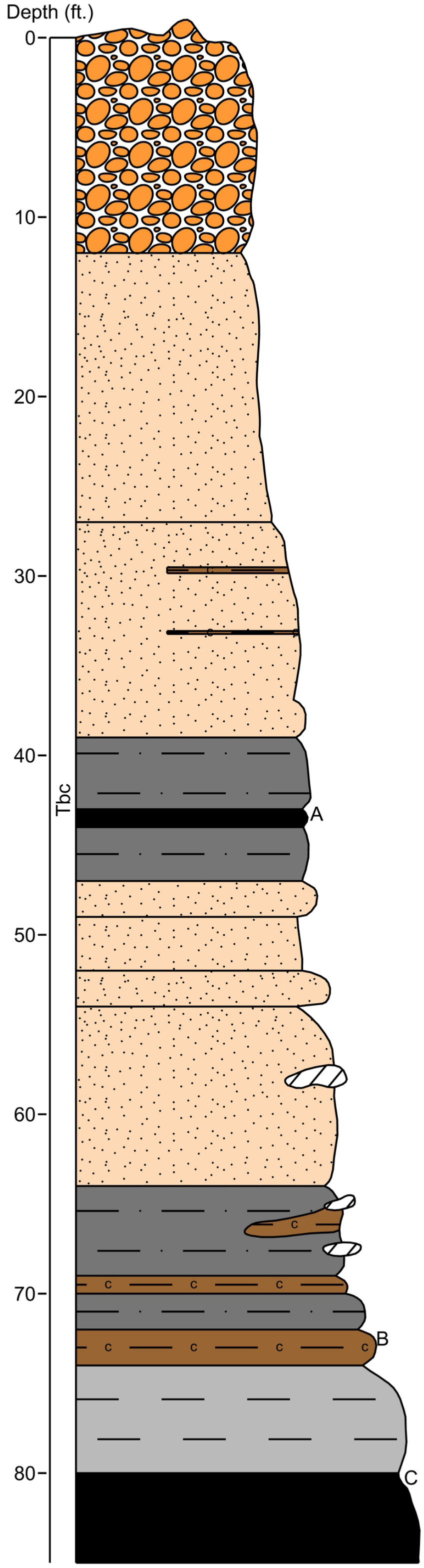
APPENDIX A

Legend and Abbreviations for Measured Sections

- Gravel
- Sandstone
- Siltstone
- Claystone
- Mudstone
- Carbonaceous Claystone
- Carbonaceous Mudstone
- Lignite
- Tonstein
- Nodules and Concretions
- Covered

REE Section 67

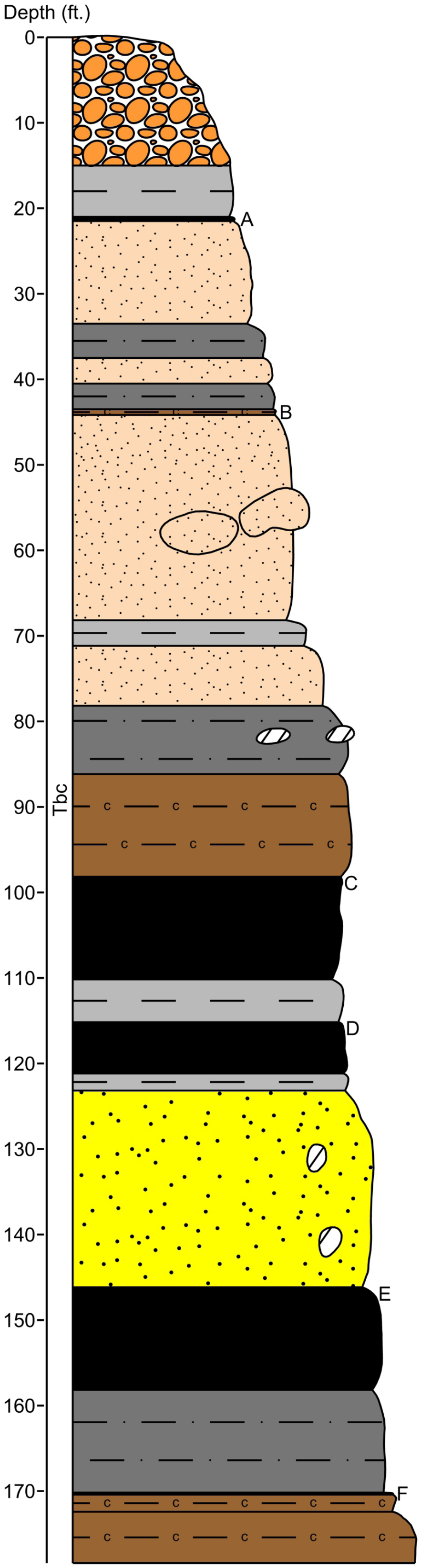
T. 136N., R. 102W., Sec. 8, NE 1/4
Elevation at top 2,656 ft.



Sample ID	Lab Analysis (in µg/g)																	Outlook coefficient
																Total REE		
	Cerium	Dysprosium	Erbium	Europium	Gadolinium	Holmium	Lanthanum	Lutetium	Neodymium	Praseodymium	Samarium	Scandium	Terbium	Thulium	Ytterbium	Yttrium	Whole coal	Ash	
67A	26.2	8.0	5.38	1.18	5.9	1.77	13.5	0.80	14.2	3.4	4.0	23.2	1.15	0.77	5.03	44	158	276	2.14
67B	70.6	4.9	2.78	1.26	5.8	0.93	33.9	0.39	31.9	8.5	6.3	12.9	0.82	0.37	2.67	26	210	241	0.90
67C	23.3	4.4	2.82	0.74	3.7	0.94	10.0	0.39	11.7	2.9	2.9	7.8	0.68	0.39	2.53	26	101	431	1.68

REE Section 68

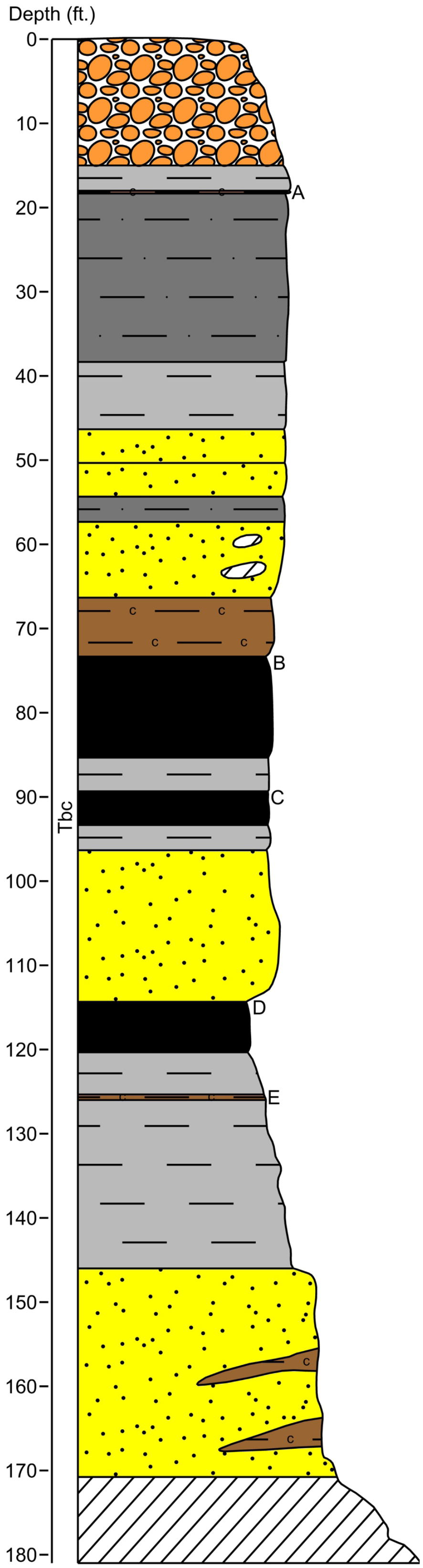
T. 136N., R. 102W., Sec. 8, NE
Elevation at top 2,667 ft.



Sample ID	Lab Analysis (in µg/g)																Outlook coefficient
	Cerium	Dysprosium	Erbium	Europium	Gadolinium	Holmium	Lanthanum	Lutetium	Neodymium	Praseodymium	Samarium	Scandium	Terbium	Thulium	Ytterbium	Yttrium	Total REE Whole coal	Total REE Ash	
68A	42.4	11.4	7.97	1.67	8.5	2.57	19.0	1.20	23.9	5.7	6.4	26.5	1.64	1.15	7.44	65	232	511	2.04
68B	27.3	6.0	4.16	0.96	4.5	1.33	14.9	0.64	13.1	3.3	3.3	18.6	0.85	0.60	4.00	33	137	277	1.71
68C	14.6	2.6	1.65	0.46	2.3	0.56	6.9	0.23	7.1	1.8	1.8	5.0	0.41	0.23	1.46	17	64	239	1.71
68D	39.6	6.9	4.11	1.24	6.1	1.42	20.1	0.56	19.2	4.9	4.6	15.7	1.09	0.57	3.60	38	168	502	1.54
68E	76.9	4.2	2.04	1.63	5.9	0.73	33.9	0.27	38.5	10.1	7.9	12.9	0.82	0.27	1.81	16	214	640	0.79
68F	205	19.0	9.27	5.65	23.4	3.48	90.6	1.07	110	26.7	25.3	19.9	3.46	1.24	7.65	86	638	824	1.07

REE Section 69

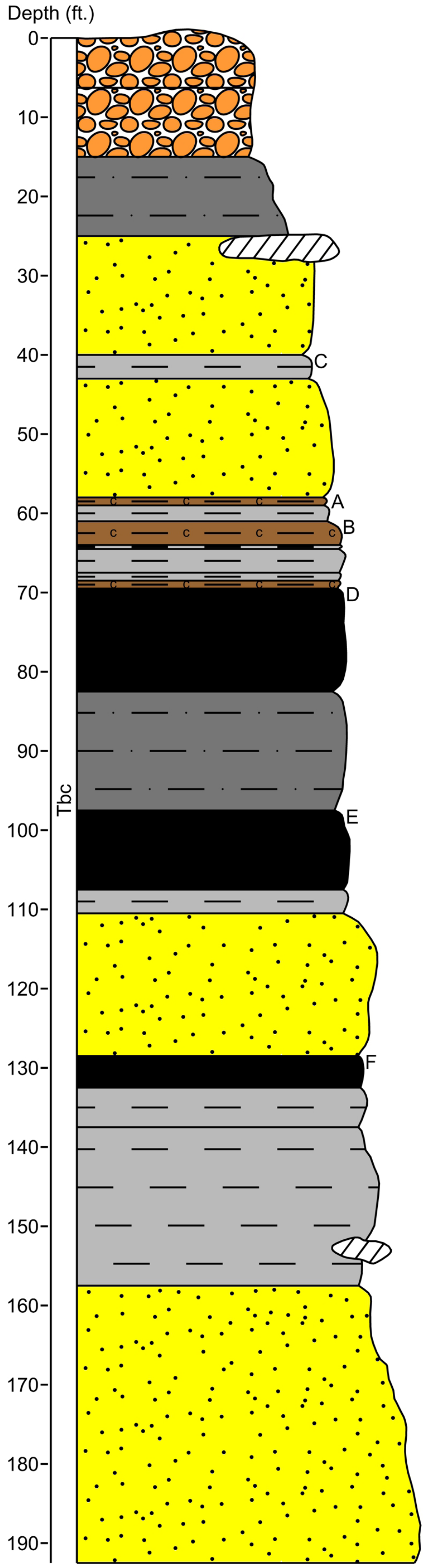
T. 136N., R. 102W., Sec. 8, NE
Elevation at top 2,654 ft.



Sample ID	Lab Analysis (in µg/g)																Total REE		Outlook coefficient
	Cerium	Dysprosium	Erbium	Europium	Gadolinium	Holmium	Lanthanum	Lutetium	Neodymium	Praseodymium	Samarium	Scandium	Terbium	Thulium	Ytterbium	Yttrium	Whole coal	Ash	
69A	71.9	13.2	9.29	2.01	10.1	2.97	33.9	1.37	34.9	8.9	8.2	29.1	1.88	1.32	8.57	81	319	399	1.65
69B	17.1	3.1	1.95	0.59	2.7	0.66	7.9	0.27	8.5	2.1	2.0	4.7	0.47	0.27	1.72	20	74	258	1.73
69C	27.4	10.2	5.91	2.03	9.5	2.10	9.6	0.80	24.8	4.8	7.7	13.3	1.66	0.83	5.16	53	179	698	2.69
69D	10.1	1.3	0.78	0.30	1.3	0.25	4.1	0.10	5.7	1.4	1.3	4.8	0.19	0.09	0.76	6	38	86	1.26
69E	59.4	3.0	1.78	0.88	3.8	0.55	29.8	0.24	26.9	7.1	4.9	14.3	0.50	0.24	1.82	16	171	206	0.79

REE Section 70

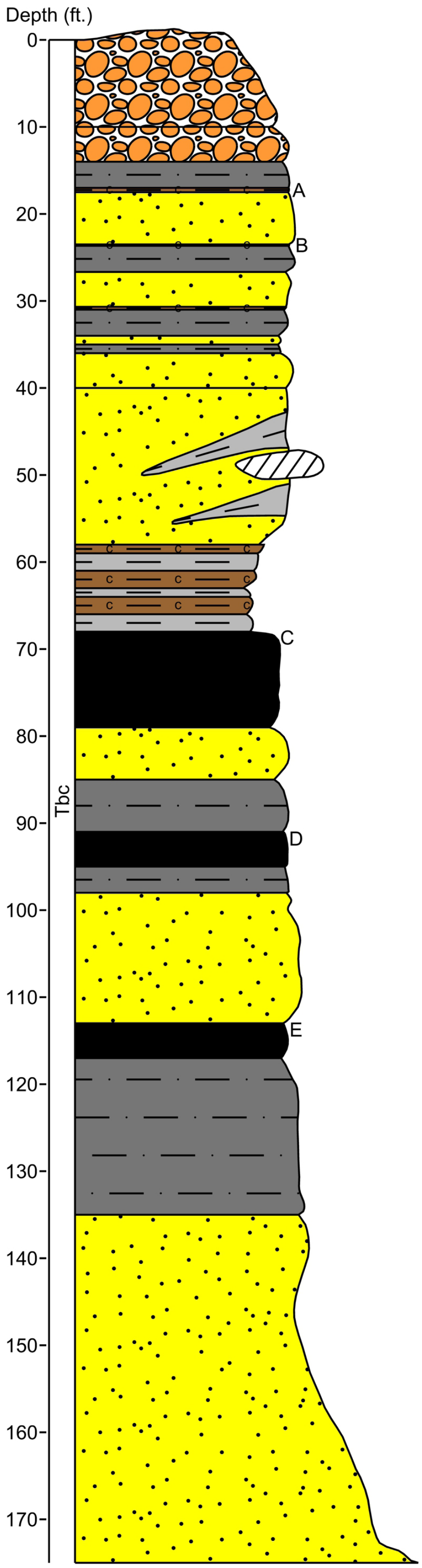
T. 136N., R. 102W., Sec. 8, NW
Elevation at top 2,674 ft.



Sample ID	Lab Analysis (in µg/g)																		Outlook coefficient
	Cerium	Dysprosium	Erbium	Europium	Gadolinium	Holmium	Lanthanum	Lutetium	Neodymium	Praseodymium	Samarium	Scandium	Terbium	Thulium	Ytterbium	Yttrium	Total REE		
																	Whole coal	Ash	
70C	53.6	3.0	1.77	0.86	3.9	0.55	25.7	0.22	24.2	6.4	4.6	8.5	0.51	0.22	1.66	16	152	169	0.82
70A	51.0	3.0	1.80	0.85	3.5	0.56	24.6	0.26	23.1	6.1	4.4	10.9	0.48	0.24	1.86	16	149	175	0.84
70B	62.6	4.1	2.43	1.05	5.0	0.79	30.5	0.31	29.0	7.5	5.5	11.9	0.69	0.31	2.32	23	187	227	0.91
70D	33.1	3.0	1.83	0.70	3.3	0.59	14.7	0.27	15.9	4.1	3.4	8.6	0.50	0.25	1.82	16	108	232	1.05
70E	12.7	2.4	1.60	0.42	2.1	0.53	5.7	0.25	6.7	1.6	1.6	6.5	0.36	0.23	1.55	15	59	275	1.74
70F	12.0	2.5	1.61	0.34	1.9	0.50	6.3	0.23	6.0	1.5	1.5	7.6	0.34	0.22	1.64	13	57	150	1.63

REE Section 71

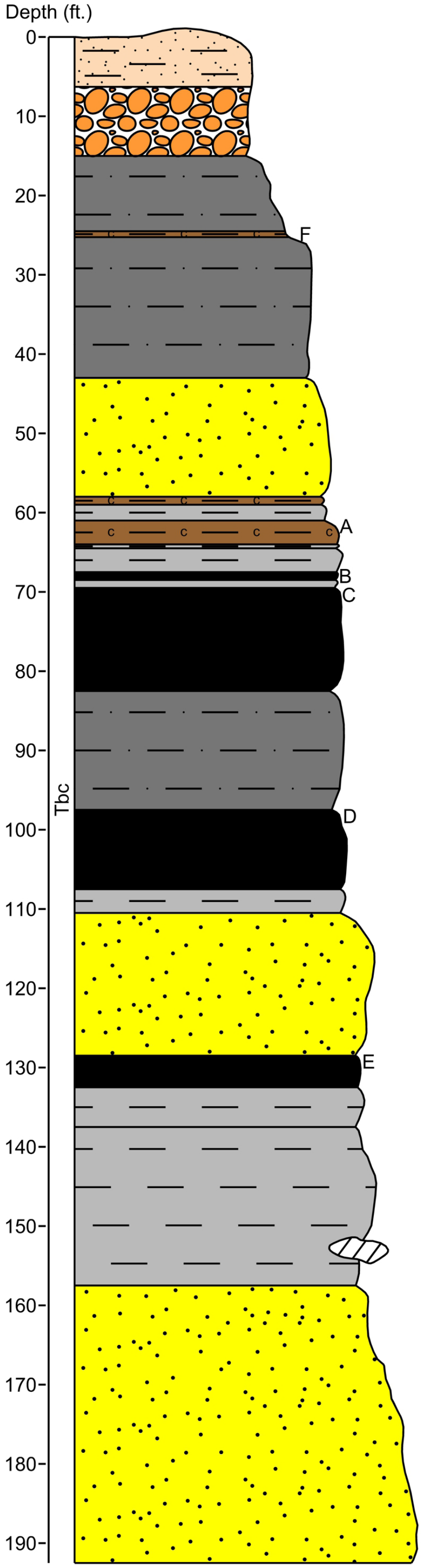
T. 136N., R. 102W., Sec. 5, SE
Elevation at top 2,657 ft.



Sample ID	Lab Analysis (in µg/g)																Total REE		Outlook coefficient
	Cerium	Dysprosium	Erbium	Europium	Gadolinium	Holmium	Lanthanum	Lutetium	Neodymium	Praseodymium	Samarium	Scandium	Terbium	Thulium	Ytterbium	Yttrium	Whole coal	Ash	
71A	49.0	10.0	7.07	1.51	7.7	2.23	24.8	1.08	25.8	6.4	6.2	23.7	1.41	1.00	6.91	59	234	346	1.74
71B	44.1	4.3	3.02	0.89	4.0	0.93	22.1	0.44	20.1	5.2	4.0	11.1	0.62	0.41	3.00	29	153	195	1.19
71C	21.9	2.0	1.27	0.50	2.1	0.42	10.0	0.21	10.2	2.6	2.2	7.5	0.34	0.19	1.28	11	74	177	1.05
71D	9.6	1.7	0.99	0.39	1.7	0.33	3.4	0.16	6.0	1.4	1.6	6.9	0.27	0.14	1.00	8	44	243	1.54
71E	17.6	1.1	0.59	0.40	1.4	0.20	7.4	0.09	9.0	2.2	1.9	7.2	0.19	0.08	0.57	4	54	147	0.82

REE Section 72

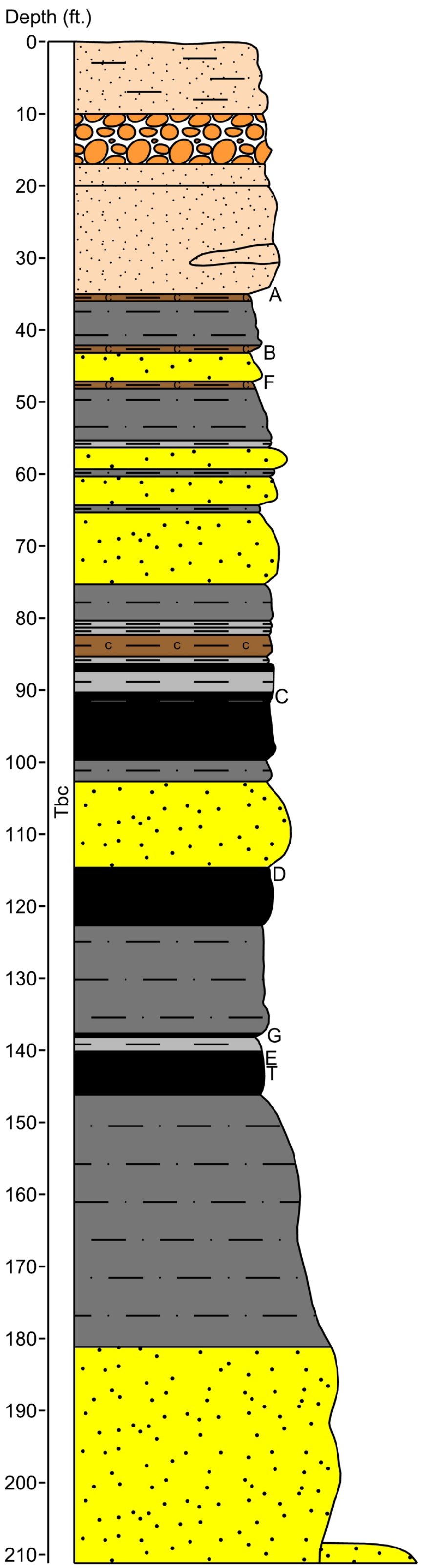
T. 136N., R. 102W., Sec. 8, NE
Elevation at top 2,668 ft.



Sample ID	Lab Analysis (in µg/g)																Total REE		Outlook coefficient
	Cerium	Dysprosium	Erbium	Europium	Gadolinium	Holmium	Lanthanum	Lutetium	Neodymium	Praseodymium	Samarium	Scandium	Terbium	Thulium	Ytterbium	Yttrium	Whole coal	Ash	
72F	49.7	5.6	3.85	1.08	5.2	1.24	24.7	0.60	23.4	6.0	4.9	13.9	0.86	0.57	3.72	36	181	264	1.27
72A	59.0	4.3	2.46	1.01	4.5	0.81	28.6	0.39	26.2	6.9	5.2	12.7	0.69	0.38	2.47	22	178	205	0.90
72B	61.6	4.0	2.44	1.05	4.8	0.80	29.5	0.36	27.6	7.2	5.4	12.2	0.70	0.36	2.32	22	182	219	0.88
72C	43.5	4.6	2.81	1.00	4.7	0.95	18.7	0.41	20.9	5.3	4.6	9.6	0.78	0.40	2.65	24	145	264	1.13
72D	25.6	5.5	3.36	1.02	5.1	1.13	11.4	0.45	14.5	3.4	3.8	11.6	0.86	0.46	2.92	33	124	478	1.91
72E	21.3	4.2	2.66	0.66	3.3	0.88	11.0	0.39	9.9	2.5	2.6	13.3	0.62	0.38	2.53	24	100	405	1.65

REE Section 73

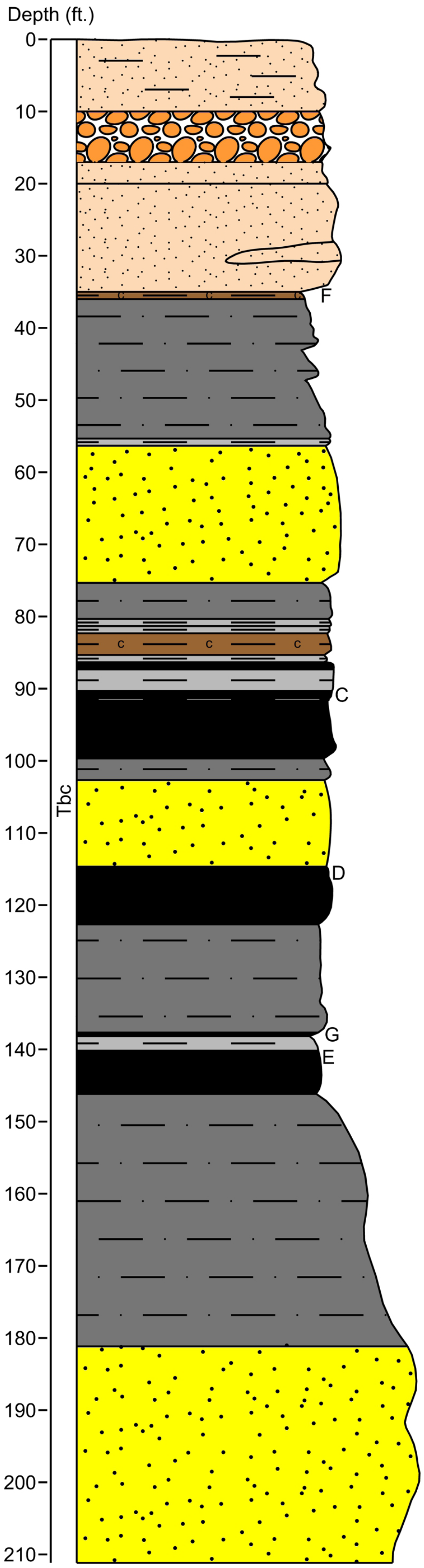
T. 136N., R. 102W., Sec. 5, SW
Elevation at top 2,678 ft.



Sample ID	Cerium	Dysprosium	Erbium	Europium	Gadolinium	Holmium	Lanthanum	Lutetium	Neodymium	Praseodymium	Samarium	Scandium	Terbium	Thulium	Ytterbium	Yttrium	Total REE Whole coal	Total REE Ash	Outlook coefficient
	Lab Analysis (in µg/g)																		
73A	19.7	5.5	3.92	0.78	3.9	1.24	9.7	0.60	10.8	2.5	2.9	14.1	0.77	0.57	3.80	32	113	222	2.08
73B	45.7	4.2	2.95	0.94	4.0	0.96	22.8	0.53	20.5	5.4	4.1	12.4	0.70	0.49	2.93	26	155	202	1.09
73F	58.0	3.6	2.31	1.00	4.1	0.75	28.7	0.35	25.3	6.8	4.8	12.0	0.60	0.35	2.35	20	171	187	0.85
73C	31.6	3.0	1.91	0.65	3.0	0.62	14.8	0.31	14.6	3.7	3.1	9.7	0.47	0.28	1.93	16	106	230	1.05
73D	11.5	2.4	1.63	0.43	1.9	0.51	5.0	0.26	6.6	1.6	1.6	7.6	0.35	0.24	1.63	14	57	368	1.80
73G	43.8	3.6	2.17	0.90	3.8	0.70	20.0	0.35	19.5	5.1	4.0	13.1	0.59	0.32	2.19	16	136	485	0.90
73E	18.9	3.2	2.20	0.51	2.6	0.70	9.5	0.35	8.5	2.1	2.1	9.7	0.47	0.33	2.20	19	82	357	1.51
73T	150	3.5	1.34	0.76	6.0	0.52	68.9	0.13	52.8	15.8	8.8	1.6	0.75	0.16	0.98	13	325	408	0.48

REE Section 74

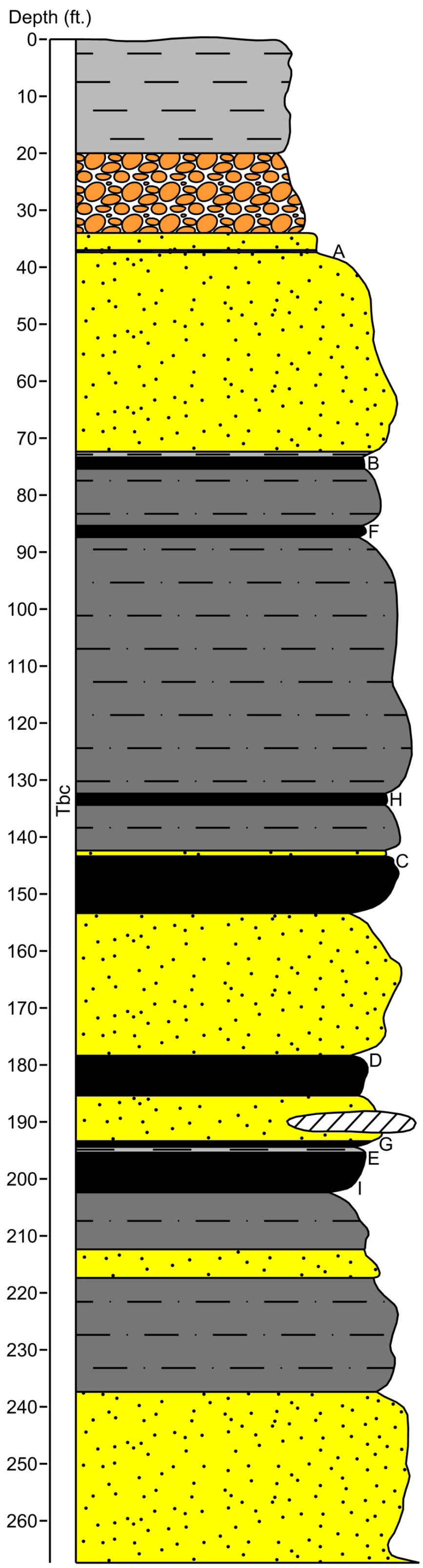
T. 136N., R. 102W., Sec. 5, SW
Elevation at top 2,667 ft.



Sample ID	Lab Analysis (in µg/g)															Total REE		Outlook coefficient
	Cerium	Dysprosium	Erbium	Europium	Gadolinium	Holmium	Lanthanum	Lutetium	Neodymium	Praseodymium	Samarium	Scandium	Terbium	Thulium	Ytterbium	Yttrium	Whole coal	Ash	
74F	53.4	5.4	3.50	1.13	5.0	1.14	25.8	0.56	23.6	6.2	4.9	15.8	0.85	0.53	3.42	29	180	248	1.08
74C	46.9	2.5	1.47	0.70	3.1	0.47	21.5	0.23	20.5	5.5	3.9	8.1	0.43	0.22	1.52	13	130	184	0.78
74D	26.7	5.9	3.68	1.10	5.1	1.21	10.6	0.54	17.1	3.9	4.4	9.4	0.90	0.53	3.47	34	129	696	1.93
74G	50.2	3.2	1.72	0.95	3.9	0.60	23.8	0.24	20.5	5.5	4.2	6.8	0.57	0.24	1.57	15	139	376	0.79
74E	44.6	4.1	2.56	0.71	3.7	0.85	26.6	0.37	15.2	4.3	3.1	9.1	0.63	0.36	2.38	26	145	512	1.01

REE Section 75

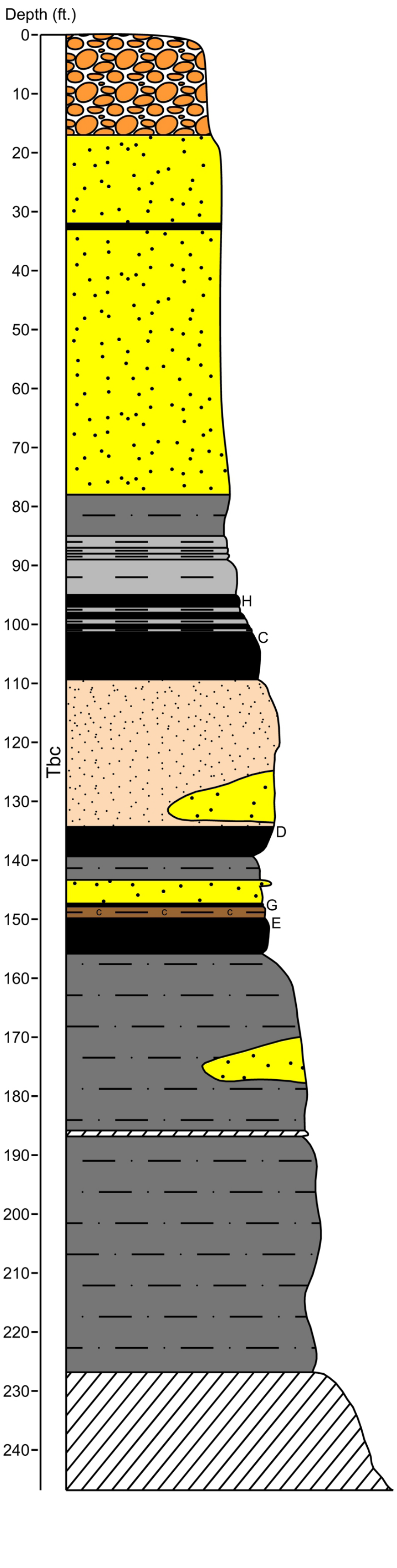
T. 136N., R. 102W., Sec. 5, SW
Elevation at top 2,709 ft.



Sample ID	Lab Analysis (in µg/g)															Total REE		Outlook coefficient
	Cerium	Dysprosium	Erbium	Europium	Gadolinium	Holmium	Lanthanum	Lutetium	Neodymium	Praseodymium	Samarium	Scandium	Terbium	Thulium	Ytterbium	Yttrium	Whole coal	Ash	
75A	71.8	4.2	2.47	1.11	4.9	0.81	34.1	0.39	31.1	8.2	5.9	12.5	0.73	0.38	2.65	22	203	213	0.81
75B	56.1	4.3	2.67	1.04	4.6	0.87	26.6	0.41	24.9	6.6	4.9	13.2	0.70	0.39	2.70	23	173	232	0.94
75F	12.8	2.6	1.82	0.43	2.1	0.58	6.2	0.25	6.8	1.6	1.7	4.9	0.37	0.25	1.56	20	64	204	2.07
75H	33.7	2.9	1.82	0.68	3.2	0.59	15.1	0.27	15.6	4.0	3.3	8.0	0.48	0.25	1.74	18	110	247	1.08
75C	20.4	3.5	2.32	0.51	2.6	0.76	13.4	0.34	7.9	2.1	1.9	8.5	0.49	0.33	2.20	23	90	540	1.57
75D	7.7	1.1	0.73	0.27	1.0	0.24	3.7	0.13	3.9	1.0	0.9	5.0	0.16	0.11	0.78	6	33	146	1.36
75G	20.0	2.2	1.30	0.62	2.4	0.42	8.2	0.21	11.9	2.8	2.7	8.7	0.37	0.19	1.32	10	73	271	1.19
75E	18.4	3.6	2.33	0.59	3.0	0.76	8.7	0.35	9.1	2.2	2.4	9.2	0.53	0.34	2.29	23	87	317	1.77
75I	12.1	1.7	1.07	0.28	1.4	0.36	6.4	0.15	5.1	1.4	1.2	3.0	0.25	0.15	0.95	11	47	275	1.42

REE Section 76

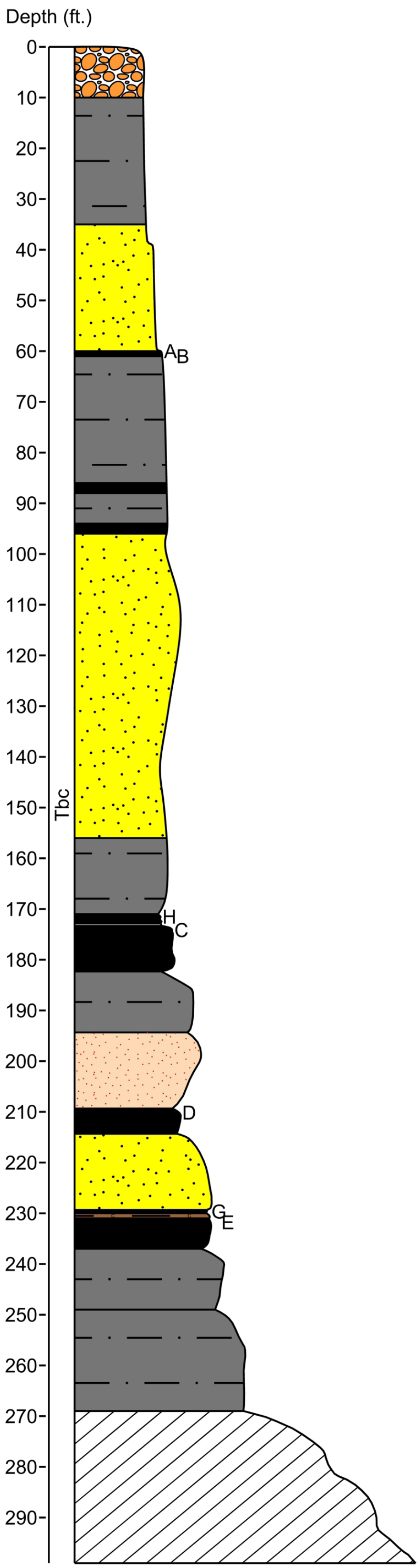
T. 136N., R. 102W., Sec. 5, SW
Elevation at top 2,678 ft.



Sample ID	Lab Analysis (in µg/g)																	Outlook coefficient
	Cerium	Dysprosium	Erbium	Europium	Gadolinium	Holmium	Lanthanum	Lutetium	Neodymium	Praseodymium	Samarium	Scandium	Terbium	Thulium	Ytterbium	Yttrium	Total REE	
																	Whole coal	Ash	
76H	29.9	3.1	1.96	0.63	3.1	0.64	13.5	0.29	13.9	3.6	2.9	7.1	0.49	0.28	1.85	18	101	268	1.16
76C	9.0	1.0	0.59	0.20	0.9	0.20	4.3	0.09	4.2	1.1	0.9	3.0	0.16	0.09	0.56	6	32	171	1.22
76D	11.6	2.9	1.95	0.46	2.2	0.63	5.3	0.29	6.3	1.5	1.6	6.0	0.41	0.28	1.84	18	61	597	2.05
76G	57.3	3.8	2.11	1.19	4.6	0.70	25.2	0.33	26.6	6.7	5.5	9.9	0.68	0.30	2.14	15	162	496	0.81
76E	50.9	3.6	2.18	0.72	3.7	0.73	25.4	0.30	17.4	5.0	3.3	6.7	0.59	0.31	1.95	21	144	652	0.84

REE Section 77

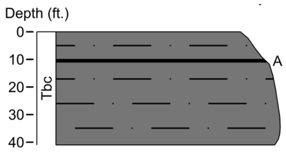
T. 136N., R. 102W., Sec. 5, SW
Elevation at top 2,730 ft.



Sample ID	Lab Analysis (in µg/g)																	Outlook coefficient
	Cerium	Dysprosium	Erbium	Europium	Gadolinium	Holmium	Lanthanum	Lutetium	Neodymium	Praseodymium	Samarium	Scandium	Terbium	Thulium	Ytterbium	Yttrium	Total REE	
																	Whole coal	Ash	
77A	66.6	9.2	6.14	1.74	8.4	1.99	35.6	0.92	33.4	8.2	7.4	19.1	1.41	0.89	5.82	58	265	347	1.44
77B	30.7	6.9	4.27	1.21	6.1	1.44	17.6	0.57	18.3	4.2	4.7	15.5	1.05	0.59	3.73	42	159	443	1.99
77H	38.1	4.3	2.78	0.84	4.1	0.92	18.1	0.40	18.0	4.6	3.8	8.5	0.67	0.40	2.58	30	138	340	1.33
77C	15.9	1.6	1.00	0.35	1.5	0.33	7.4	0.14	7.0	1.8	1.4	4.2	0.26	0.14	0.93	10	54	207	1.16
77D	16.5	3.7	2.36	0.68	3.2	0.77	6.5	0.37	9.9	2.2	2.6	7.6	0.57	0.34	2.30	18	78	482	1.74
77G	55.7	9.1	4.81	2.65	10.5	1.69	15.7	0.69	47.6	10.1	11.3	23.8	1.57	0.69	4.57	36	236	959	1.61
77E	75.8	5.9	3.75	1.16	5.6	1.22	32.3	0.54	27.2	7.4	5.4	9.9	0.93	0.53	3.45	35	216	631	0.91

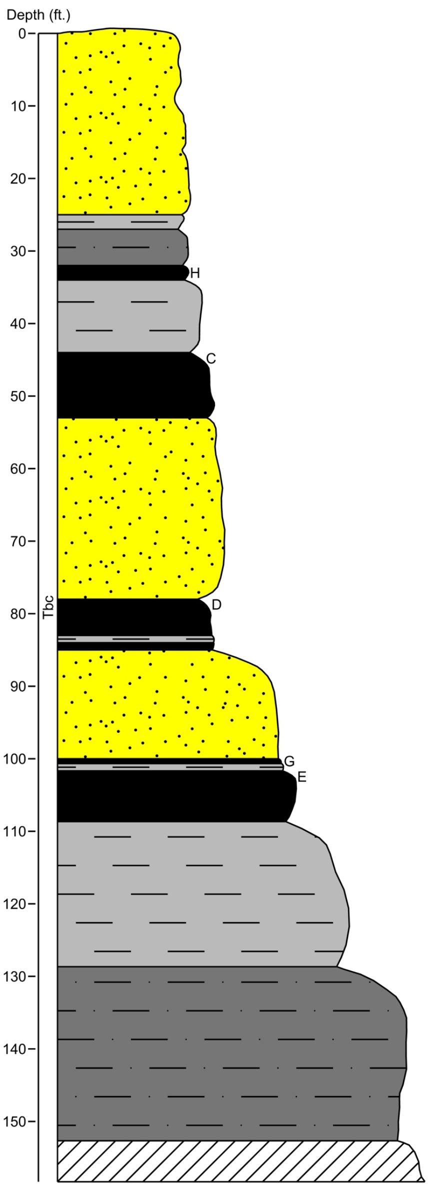
REE Section 78

T. 136N., R. 102W., Sec. 5, SW
Elevation at top 2,841 ft.



REE Section 79

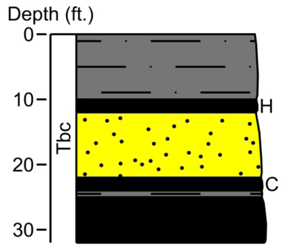
T. 136N., R. 102W., Sec. 5, SW
Elevation at top 2,627 ft.



Sample ID	Lab Analysis (in µg/g)																	Outlook coefficient
	Cerium	Dysprosium	Erbium	Europium	Gadolinium	Holmium	Lanthanum	Lutetium	Neodymium	Praseodymium	Samarium	Scandium	Terbium	Thulium	Ytterbium	Yttrium	Total REE	
																	Whole coal	Ash	
78A	23.3	2.9	1.44	1.16	3.6	0.52	7.0	0.21	16.9	3.7	4.1	5.7	0.52	0.20	1.37	9	82	181	1.25
79H	17.3	1.4	0.86	0.40	1.6	0.28	8.1	0.13	8.2	2.1	1.8	3.9	0.24	0.12	0.83	7	54	144	0.97
79C	37.7	3.7	2.09	0.76	3.6	0.73	18.3	0.27	15.2	4.1	3.3	7.3	0.60	0.28	1.79	21	121	569	1.06
79D	10.6	1.2	0.69	0.39	1.3	0.23	3.9	0.11	5.9	1.4	1.5	5.0	0.20	0.10	0.72	5	38	96	1.14
79G	28.2	3.7	2.01	1.16	4.5	0.69	8.2	0.29	22.5	4.9	5.1	10.0	0.66	0.29	1.96	15	109	582	1.43
79E	46.1	5.2	3.27	0.95	4.7	1.08	22.2	0.47	18.5	4.9	4.1	9.5	0.79	0.47	3.07	30	155	488	1.15

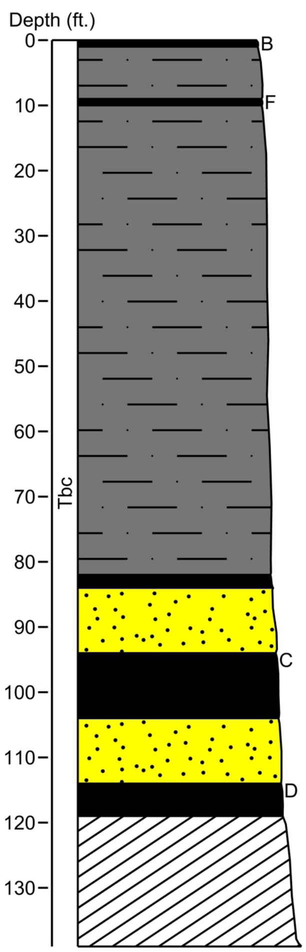
REE Section 80

T. 136N., R. 102W., Sec. 5, SW
Elevation at top 2,592 ft.



REE Section 81

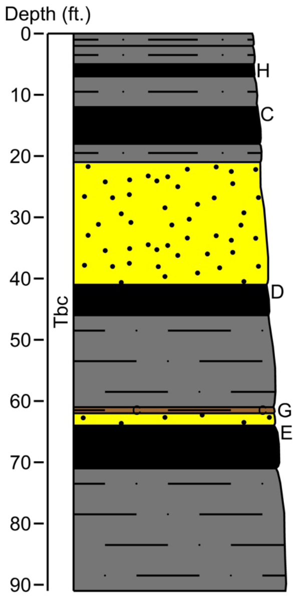
T. 136N., R. 102W., Sec. 6, SE
Elevation at top 2,578 ft.



Sample ID	Lab Analysis (in µg/g)																	Outlook coefficient
	Cerium	Dysprosium	Erbium	Europium	Gadolinium	Holmium	Lanthanum	Lutetium	Neodymium	Praseodymium	Samarium	Scandium	Terbium	Thulium	Ytterbium	Yttrium	Total REE Whole coal	Total REE Ash	
80H	25.3	2.6	1.64	0.56	2.6	0.54	12.5	0.23	11.8	3.0	2.5	5.3	0.40	0.23	1.45	18	89	231	1.26
80C	15.1	3.3	2.22	0.54	2.5	0.71	6.9	0.32	7.7	1.9	1.8	9.4	0.46	0.32	2.11	21	76	323	1.90
81B	46.7	3.2	1.93	0.91	3.6	0.65	22.2	0.31	21.0	5.5	4.3	11.0	0.53	0.29	2.03	15	139	196	0.85
81F	22.5	2.6	1.72	0.51	2.5	0.57	10.4	0.23	10.7	2.8	2.2	4.3	0.41	0.23	1.49	20	83	325	1.44
81C	26.9	4.9	3.32	0.82	3.8	1.07	13.6	0.50	12.0	3.1	2.9	13.9	0.69	0.48	3.19	32	123	485	1.67
81D	20.5	5.1	3.96	0.80	3.6	1.20	9.5	0.68	10.9	2.7	2.8	18.9	0.69	0.60	4.16	33	119	627	2.01

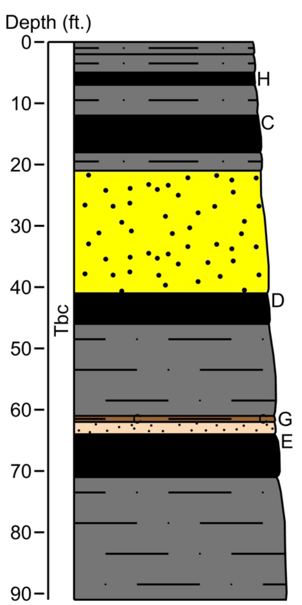
REE Section 82

T. 136N., R. 102W., Sec. 6, SE
Elevation at top 2,567 ft.



REE Section 83

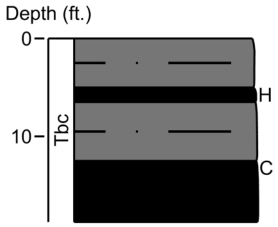
T. 136N., R. 102W., Sec. 6, SE
Elevation at top 2,563 ft.



Sample ID	Lab Analysis (in µg/g)																		Outlook coefficient
	Cerium	Dysprosium	Erbium	Europium	Gadolinium	Holmium	Lanthanum	Lutetium	Neodymium	Praseodymium	Samarium	Scandium	Terbium	Thulium	Ytterbium	Yttrium	Total REE Whole coal	Total REE Ash	
82H	42.0	3.7	2.15	0.94	4.1	0.72	17.9	0.31	20.7	5.2	4.4	9.3	0.62	0.31	2.04	18	132	229	1.02
82C	31.9	4.5	2.41	0.94	4.3	0.87	15.6	0.28	14.6	3.8	3.7	9.6	0.74	0.32	1.95	24	120	459	1.34
82D	35.9	6.1	3.65	1.30	5.8	1.24	17.1	0.52	21.0	5.0	5.1	14.0	0.98	0.50	3.35	30	152	672	1.52
82G	77.2	5.3	2.75	1.70	6.3	0.95	34.5	0.41	37.9	9.8	8.0	17.0	0.95	0.40	2.75	21	227	256	0.85
82E	64.4	6.7	3.21	2.40	8.8	1.16	17.8	0.43	47.5	10.8	11.3	20.0	1.24	0.44	2.90	24	223	582	1.23
83H	38.7	3.2	1.85	0.88	3.7	0.62	16.5	0.28	19.3	4.8	4.1	7.3	0.54	0.27	1.83	16	120	231	1.00
83C	81.1	9.3	4.96	2.06	9.5	1.79	37.2	0.64	38.6	9.8	8.5	16.0	1.55	0.67	4.25	49	275	1032	1.19
83D	29.2	4.7	2.87	1.01	4.4	0.95	9.0	0.45	15.9	3.6	4.2	8.5	0.75	0.42	2.87	21	110	639	1.36
83G	63.8	3.4	1.83	1.13	4.0	0.62	25.4	0.28	25.2	6.6	4.9	12.0	0.61	0.27	1.87	14	166	181	0.69
83E	36.0	3.6	1.87	1.20	4.4	0.66	11.6	0.27	23.4	5.5	5.3	11.4	0.63	0.26	1.76	14	122	322	1.15

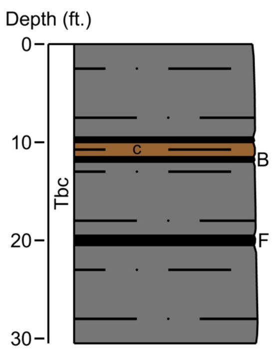
REE Section 84

T. 136N., R. 102W., Sec. 6, SE
Elevation at top 2,573 ft.



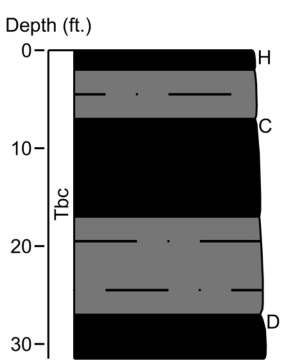
REE Section 85

T. 136N., R. 102W., Sec. 6, SE
Elevation at top 2,657 ft.



REE Section 86

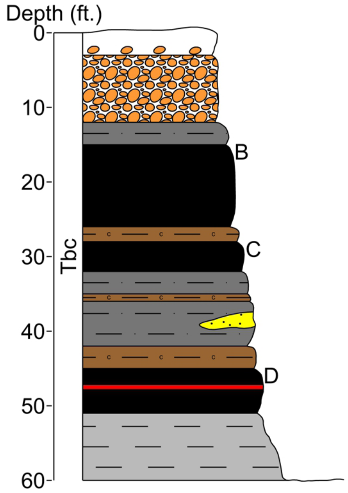
T. 136N., R. 102W., Sec. 6, SE
Elevation at top 2,583 ft.



Sample ID	Lab Analysis (in µg/g)																		Outlook coefficient
	Cerium	Dysprosium	Erbium	Europium	Gadolinium	Holmium	Lanthanum	Lutetium	Neodymium	Praseodymium	Samarium	Scandium	Terbium	Thulium	Ytterbium	Yttrium	Total REE Whole coal	Total REE Ash	
84H	53.8	4.1	2.36	1.06	4.6	0.79	23.5	0.36	25.0	6.4	5.1	9.0	0.69	0.33	2.29	21	160	267	0.94
84C	20.0	4.1	2.67	0.71	3.2	0.88	9.4	0.39	9.6	2.4	2.4	9.7	0.59	0.38	2.52	27	96	327	1.85
85B	50.5	3.8	2.36	0.91	4.1	0.75	23.5	0.35	22.9	5.9	4.6	11.6	0.63	0.34	2.29	20	155	222	0.93
85F	40.8	3.6	2.22	1.10	4.0	0.74	18.4	0.31	19.6	5.0	4.0	7.3	0.60	0.30	1.99	22	132	255	1.11
86H	42.7	3.5	2.15	0.90	4.0	0.70	17.8	0.32	20.3	5.1	4.2	8.6	0.59	0.31	2.07	19	132	262	1.01
86C	70.1	6.3	3.76	1.21	6.3	1.30	45.0	0.48	25.7	7.1	4.9	9.9	1.00	0.51	3.15	46	233	523	1.11
86D	12.5	3.8	3.08	0.54	2.6	0.93	6.9	0.53	6.7	1.6	1.7	13.9	0.51	0.46	3.16	30	89	571	2.54

REE Section 87

T. 136N., R. 102W., Sec. 7, SE/SE
Elevation at top 2,600 ft.

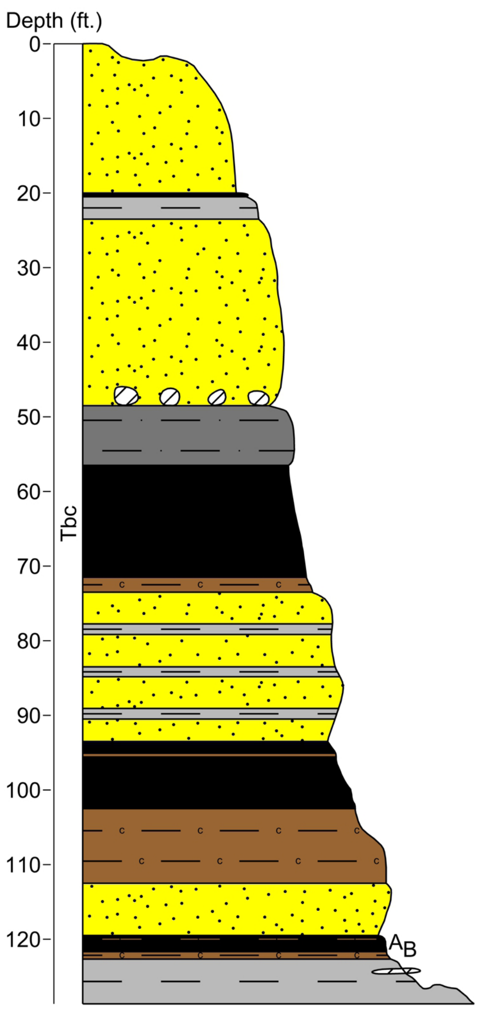


Sample ID	Lab Analysis (in µg/g)															Total REE		Outlook coefficient
	Cerium	Dysprosium	Erbium	Europium	Gadolinium	Holmium	Lanthanum	Lutetium	Neodymium	Praseodymium	Samarium	Scandium	Terbium	Thulium	Ytterbium	Yttrium	Whole coal	Ash	
87B	51.00	10.10	5.48	2.36	10.40	1.97	14.30	0.75	40.80	8.94	10.90	18.40	1.73	0.79	5.09	44.30	227	521	1.76
87C	75.81	8.89	4.68	2.15	9.82	1.70	39.77	0.59	41.85	10.58	9.25	15.22	1.58	0.65	4.14	34.66	261	1262	1.13
87D	99.58	6.28	3.04	2.21	8.52	1.11	44.64	0.39	49.68	12.46	10.66	18.48	1.20	0.42	2.74	22.03	283	446	0.81

For Sections 88-96, see Figure 19 and Appendix B.

REE Section 97

T. 136N., R. 102W., Sec. 16, NE/SW/NE
Elevation at top 2,616 ft.



Sample ID	Lab Analysis (in µg/g)															Total REE		Outlook coefficient
	Cerium	Dysprosium	Erbium	Europium	Gadolinium	Holmium	Lanthanum	Lutetium	Neodymium	Praseodymium	Samarium	Scandium	Terbium	Thulium	Ytterbium	Yttrium	Whole coal	Ash	
97A	355.13	26.10	9.22	10.18	39.65	3.97	167.55	0.77	198.07	50.08	44.00	32.29	5.44	1.10	6.28	76.58	1026	1718	0.89
97B	178.11	14.09	6.73	4.46	18.57	2.55	92.63	0.69	97.65	24.62	19.59	16.06	2.63	0.88	5.19	54.40	539	1939	0.96

Appendix B. Rare Earth Concentrations and Outlook Coefficients

Concentrations are reported as µg/g or parts per million.

* Denotes duplicate sample analysis

																	ΣREE		
NDGS ID	**Ce**	**Dy**	**Er**	**Eu**	**Gd**	**Ho**	**La**	**Lu**	**Nd**	**Pr**	**Sm**	**Sc**	**Tb**	**Tm**	**Yb**	**Y**	**Whole**	**Ash**	C_{outl}
67A	26.2	8.0	5.38	1.18	5.9	1.77	13.5	0.80	14.2	3.4	4.0	23.2	1.15	0.77	5.03	44	**158**	**276**	2.14
67B	70.6	4.9	2.78	1.26	5.8	0.93	33.9	0.39	31.9	8.5	6.3	12.9	0.82	0.37	2.67	26	**210**	**241**	0.90
67C	23.3	4.4	2.82	0.74	3.7	0.94	10.0	0.39	11.7	2.9	2.9	7.8	0.68	0.39	2.53	26	**101**	**431**	1.68
68A	42.4	11.4	7.97	1.67	8.5	2.57	19.0	1.20	23.9	5.7	6.4	26.5	1.64	1.15	7.44	65	**232**	**511**	2.04
68B	27.3	6.0	4.16	0.96	4.5	1.33	14.9	0.64	13.1	3.3	3.3	18.6	0.85	0.60	4.00	33	**137**	**277**	1.71
68C	14.6	2.6	1.65	0.46	2.3	0.56	6.9	0.23	7.1	1.8	1.8	5.0	0.41	0.23	1.46	17	**64**	**239**	1.71
68D	39.6	6.9	4.11	1.24	6.1	1.42	20.1	0.56	19.2	4.9	4.6	15.7	1.09	0.57	3.60	38	**168**	**502**	1.54
68E	76.9	4.2	2.04	1.63	5.9	0.73	33.9	0.27	38.5	10.1	7.9	12.9	0.82	0.27	1.81	16	**214**	**640**	0.79
68F	205.0	19.0	9.27	5.65	23.4	3.48	90.6	1.07	110.0	26.7	25.3	19.9	3.46	1.24	7.65	86	**638**	**824**	1.07
69A	71.9	13.2	9.29	2.01	10.1	2.97	33.9	1.37	34.9	8.9	8.2	29.1	1.88	1.32	8.57	81	**319**	**399**	1.65
69B	17.1	3.1	1.95	0.59	2.7	0.66	7.9	0.27	8.5	2.1	2.0	4.7	0.47	0.27	1.72	20	**74**	**258**	1.73
69C	27.4	10.2	5.91	2.03	9.5	2.10	9.6	0.80	24.8	4.8	7.7	13.3	1.66	0.83	5.16	53	**179**	**698**	2.69
69D	10.1	1.3	0.78	0.30	1.3	0.25	4.1	0.10	5.7	1.4	1.3	4.8	0.19	0.09	0.76	6	**38**	**86**	1.26
69E	59.4	3.0	1.78	0.88	3.8	0.55	29.8	0.24	26.9	7.1	4.9	14.3	0.50	0.24	1.82	16	**171**	**206**	0.79
70A	51.0	3.0	1.80	0.85	3.5	0.56	24.6	0.26	23.1	6.1	4.4	10.9	0.48	0.24	1.86	16	**149**	**175**	0.84
70B	62.6	4.1	2.43	1.05	5.0	0.79	30.5	0.31	29.0	7.5	5.5	11.9	0.69	0.31	2.32	23	**187**	**227**	0.91
70C	53.6	3.0	1.77	0.86	3.9	0.55	25.7	0.22	24.2	6.4	4.6	8.5	0.51	0.22	1.66	16	**152**	**169**	0.82
70D	33.1	3.0	1.83	0.70	3.3	0.59	14.7	0.27	15.9	4.1	3.4	8.6	0.50	0.25	1.82	16	**108**	**232**	1.05
70E	12.7	2.4	1.60	0.42	2.1	0.53	5.7	0.25	6.7	1.6	1.6	6.5	0.36	0.23	1.55	15	**59**	**275**	1.74
70F	12.0	2.5	1.61	0.34	1.9	0.50	6.3	0.23	6.0	1.5	1.5	7.6	0.34	0.22	1.64	13	**57**	**150**	1.63
71A	49.0	10.0	7.07	1.51	7.7	2.23	24.8	1.08	25.8	6.4	6.2	23.7	1.41	1.00	6.91	59	**234**	**346**	1.74
71B	44.1	4.3	3.02	0.89	4.0	0.93	22.1	0.44	20.1	5.2	4.0	11.1	0.62	0.41	3.00	29	**153**	**195**	1.19
71C	21.9	2.0	1.27	0.50	2.1	0.42	10.0	0.21	10.2	2.6	2.2	7.5	0.34	0.19	1.28	11	**74**	**177**	1.05
71D	9.6	1.7	0.99	0.39	1.7	0.33	3.4	0.16	6.0	1.4	1.6	6.9	0.27	0.14	1.00	8	**44**	**243**	1.54
71E	17.6	1.1	0.59	0.40	1.4	0.20	7.4	0.09	9.0	2.2	1.9	7.2	0.19	0.08	0.57	4	**54**	**147**	0.82
72A	59.0	4.3	2.46	1.01	4.5	0.81	28.6	0.39	26.2	6.9	5.2	12.7	0.69	0.38	2.47	22	**178**	**205**	0.90
72B	61.6	4.0	2.44	1.05	4.8	0.80	29.5	0.36	27.6	7.2	5.4	12.2	0.70	0.36	2.32	22	**182**	**219**	0.88
72C	43.5	4.6	2.81	1.00	4.7	0.95	18.7	0.41	20.9	5.3	4.6	9.6	0.78	0.40	2.65	24	**145**	**264**	1.13
72D	25.6	5.5	3.36	1.02	5.1	1.13	11.4	0.45	14.5	3.4	3.8	11.6	0.86	0.46	2.92	33	**124**	**478**	1.91
72E	21.3	4.2	2.66	0.66	3.3	0.88	11.0	0.39	9.9	2.5	2.6	13.3	0.62	0.38	2.53	24	**100**	**405**	1.65
72F	49.7	5.6	3.85	1.08	5.2	1.24	24.7	0.60	23.4	6.0	4.9	13.9	0.86	0.57	3.72	36	**181**	**264**	1.27
73A	19.7	5.5	3.92	0.78	3.9	1.24	9.7	0.60	10.8	2.5	2.9	14.1	0.77	0.57	3.80	32	**113**	**222**	2.08
73B	45.7	4.2	2.95	0.94	4.0	0.96	22.8	0.53	20.5	5.4	4.1	12.4	0.70	0.49	2.93	26	**155**	**202**	1.09
73C	31.6	3.0	1.91	0.65	3.0	0.62	14.8	0.31	14.6	3.7	3.1	9.7	0.47	0.28	1.93	16	**106**	**230**	1.05
73D	11.5	2.4	1.63	0.43	1.9	0.51	5.0	0.26	6.6	1.6	1.6	7.6	0.35	0.24	1.63	14	**57**	**368**	1.80
73E	18.9	3.2	2.20	0.51	2.6	0.70	9.5	0.35	8.5	2.1	2.1	9.7	0.47	0.33	2.20	19	**82**	**357**	1.51
73F	58.0	3.6	2.31	1.00	4.1	0.75	28.7	0.35	25.3	6.8	4.8	12.0	0.60	0.35	2.35	20	**171**	**187**	0.85
73G	43.8	3.6	2.17	0.90	3.8	0.70	20.0	0.35	19.5	5.1	4.0	13.1	0.59	0.32	2.19	16	**136**	**485**	0.90
73T	150.0	3.5	1.34	0.76	6.0	0.52	68.9	0.13	52.8	15.8	8.8	1.6	0.75	0.16	0.98	13	**325**	**408**	0.48
74C	46.9	2.5	1.47	0.70	3.1	0.47	21.5	0.23	20.5	5.5	3.9	8.1	0.43	0.22	1.52	13	**130**	**184**	0.78
74D	26.7	5.9	3.68	1.10	5.1	1.21	10.6	0.54	17.1	3.9	4.4	9.4	0.90	0.53	3.47	34	**129**	**696**	1.93
74E	44.6	4.1	2.56	0.71	3.7	0.85	26.6	0.37	15.2	4.3	3.1	9.1	0.63	0.36	2.38	26	**145**	**512**	1.01
74F	53.4	5.4	3.50	1.13	5.0	1.14	25.8	0.56	23.6	6.2	4.9	15.8	0.85	0.53	3.42	29	**180**	**248**	1.08
74G	50.2	3.2	1.72	0.95	3.9	0.60	23.8	0.24	20.5	5.5	4.2	6.8	0.57	0.24	1.57	15	**139**	**376**	0.79
75A	71.8	4.2	2.47	1.11	4.9	0.81	34.1	0.39	31.1	8.2	5.9	12.5	0.73	0.38	2.65	22	**203**	**213**	0.81
75B	56.1	4.3	2.67	1.04	4.6	0.87	26.6	0.41	24.9	6.6	4.9	13.2	0.70	0.39	2.70	23	**173**	**232**	0.94
75C	20.4	3.5	2.32	0.51	2.6	0.76	13.4	0.34	7.9	2.1	1.9	8.5	0.49	0.33	2.20	23	**90**	**540**	1.57
75D	7.7	1.1	0.73	0.27	1.0	0.24	3.7	0.13	3.9	1.0	0.9	5.0	0.16	0.11	0.78	6	**33**	**146**	1.36
75E	18.4	3.6	2.33	0.59	3.0	0.76	8.7	0.35	9.1	2.2	2.4	9.2	0.53	0.34	2.29	23	**87**	**317**	1.77
75F	12.8	2.6	1.82	0.43	2.1	0.58	6.2	0.25	6.8	1.6	1.7	4.9	0.37	0.25	1.56	20	**64**	**204**	2.07
75G	20.0	2.2	1.30	0.62	2.4	0.42	8.2	0.21	11.9	2.8	2.7	8.7	0.37	0.19	1.32	10	**73**	**271**	1.19
75H	33.7	2.9	1.82	0.68	3.2	0.59	15.1	0.27	15.6	4.0	3.3	8.0	0.48	0.25	1.74	18	**110**	**247**	1.08
75I	12.1	1.7	1.07	0.28	1.4	0.36	6.4	0.15	5.1	1.4	1.2	3.0	0.25	0.15	0.95	11	**47**	**275**	1.42

Appendix B. Rare Earth Concentrations and Outlook Coefficients (continued)

																	ΣREE		
NDGS ID	**Ce**	**Dy**	**Er**	**Eu**	**Gd**	**Ho**	**La**	**Lu**	**Nd**	**Pr**	**Sm**	**Sc**	**Tb**	**Tm**	**Yb**	**Y**	**Whole**	**Ash**	C_{outl}
76C	9.0	1.0	0.59	0.20	0.9	0.20	4.3	0.09	4.2	1.1	0.9	3.0	0.16	0.09	0.56	6	**32**	**171**	1.22
76D	11.6	2.9	1.95	0.46	2.2	0.63	5.3	0.29	6.3	1.5	1.6	6.0	0.41	0.28	1.84	18	**61**	**597**	2.05
76E	50.9	3.6	2.18	0.72	3.7	0.73	25.4	0.30	17.4	5.0	3.3	6.7	0.59	0.31	1.95	21	**144**	**652**	0.84
76G	57.3	3.8	2.11	1.19	4.6	0.70	25.2	0.33	26.6	6.7	5.5	9.9	0.68	0.30	2.14	15	**162**	**496**	0.81
76H	29.9	3.1	1.96	0.63	3.1	0.64	13.5	0.29	13.9	3.6	2.9	7.1	0.49	0.28	1.85	18	**101**	**268**	1.16
77A	66.6	9.2	6.14	1.74	8.4	1.99	35.6	0.92	33.4	8.2	7.4	19.1	1.41	0.89	5.82	58	**265**	**247**	1.44
77B	30.7	6.9	4.27	1.21	6.1	1.44	17.6	0.57	18.3	4.2	4.7	15.5	1.05	0.59	3.73	42	**159**	**443**	1.99
77C	15.9	1.6	1.00	0.35	1.5	0.33	7.4	0.14	7.0	1.8	1.4	4.2	0.26	0.14	0.93	10	**54**	**207**	1.16
77D	16.5	3.7	2.36	0.68	3.2	0.77	6.5	0.37	9.9	2.2	2.6	7.6	0.57	0.34	2.30	18	**78**	**482**	1.74
77E	75.8	5.9	3.75	1.16	5.6	1.22	32.3	0.54	27.2	7.4	5.4	9.9	0.93	0.53	3.45	35	**216**	**631**	0.91
77G	55.7	9.1	4.81	2.65	10.5	1.69	15.7	0.69	47.6	10.1	11.3	23.8	1.57	0.69	4.57	36	**236**	**959**	1.61
77H	38.1	4.3	2.78	0.84	4.1	0.92	18.1	0.40	18.0	4.6	3.8	8.5	0.67	0.40	2.58	30	**138**	**340**	1.33
78A	23.3	2.9	1.44	1.16	3.6	0.52	7.0	0.21	16.9	3.7	4.1	5.7	0.52	0.20	1.37	9	**82**	**181**	1.25
79C	37.7	3.7	2.09	0.76	3.6	0.73	18.3	0.27	15.2	4.1	3.3	7.3	0.60	0.28	1.79	21	**121**	**569**	1.06
79D	10.6	1.2	0.69	0.39	1.3	0.23	3.9	0.11	5.9	1.4	1.5	5.0	0.20	0.10	0.72	5	**38**	**96**	1.14
79E	46.1	5.2	3.27	0.95	4.7	1.08	22.2	0.47	18.5	4.9	4.1	9.5	0.79	0.47	3.07	30	**155**	**488**	1.15
79G	28.2	3.7	2.01	1.16	4.5	0.69	8.2	0.29	22.5	4.9	5.1	10.0	0.66	0.29	1.96	15	**109**	**582**	1.43
79H	17.3	1.4	0.86	0.40	1.6	0.28	8.1	0.13	8.2	2.1	1.8	3.9	0.24	0.12	0.83	7	**54**	**144**	0.97
80C	15.1	3.3	2.22	0.54	2.5	0.71	6.9	0.32	7.7	1.9	1.8	9.4	0.46	0.32	2.11	21	**76**	**323**	1.90
80H	25.3	2.6	1.64	0.56	2.6	0.54	12.5	0.23	11.8	3.0	2.5	5.3	0.40	0.23	1.45	18	**89**	**231**	1.26
81B	46.7	3.2	1.93	0.91	3.6	0.65	22.2	0.31	21.0	5.5	4.3	11.0	0.53	0.29	2.03	15	**139**	**196**	0.85
81C	26.9	4.9	3.32	0.82	3.8	1.07	13.6	0.50	12.0	3.1	2.9	13.9	0.69	0.48	3.19	32	**123**	**485**	1.67
81D	20.5	5.1	3.96	0.80	3.6	1.20	9.5	0.68	10.9	2.7	2.8	18.9	0.69	0.60	4.16	33	**119**	**627**	2.01
81F	22.5	2.6	1.72	0.51	2.5	0.57	10.4	0.23	10.7	2.8	2.2	4.3	0.41	0.23	1.49	20	**83**	**325**	1.44
82C	31.9	4.5	2.41	0.94	4.3	0.87	15.6	0.28	14.6	3.8	3.7	9.6	0.74	0.32	1.95	24	**120**	**459**	1.34
82D	35.9	6.1	3.65	1.30	5.8	1.24	17.1	0.52	21.0	5.0	5.1	14.0	0.98	0.50	3.35	30	**152**	**672**	1.52
82E	64.4	6.7	3.21	2.40	8.8	1.16	17.8	0.43	47.5	10.8	11.3	20.0	1.24	0.44	2.90	24	**223**	**582**	1.23
82G	77.2	5.3	2.75	1.70	6.3	0.95	34.5	0.41	37.9	9.8	8.0	17.0	0.95	0.40	2.75	21	**227**	**256**	0.85
82H	42.0	3.7	2.15	0.94	4.1	0.72	17.9	0.31	20.7	5.2	4.4	9.3	0.62	0.31	2.04	18	**132**	**229**	1.02
83C	81.1	9.3	4.96	2.06	9.5	1.79	37.2	0.64	38.6	9.8	8.5	16.0	1.55	0.67	4.25	49	**275**	**1032**	1.19
83D	29.2	4.7	2.87	1.01	4.4	0.95	9.0	0.45	15.9	3.6	4.2	8.5	0.75	0.42	2.87	21	**110**	**639**	1.36
83E	36.0	3.6	1.87	1.20	4.4	0.66	11.6	0.27	23.4	5.5	5.3	11.4	0.63	0.26	1.76	14	**122**	**322**	1.15
83G	63.8	3.4	1.83	1.13	4.0	0.62	25.4	0.28	25.2	6.6	4.9	12.0	0.61	0.27	1.87	14	**166**	**181**	0.69
83H	38.7	3.2	1.85	0.88	3.7	0.62	16.5	0.28	19.3	4.8	4.1	7.3	0.54	0.27	1.83	16	**120**	**231**	1.00
84C	20.0	4.1	2.67	0.71	3.2	0.88	9.4	0.39	9.6	2.4	2.4	9.7	0.59	0.38	2.52	27	**96**	**327**	1.85
84H	53.8	4.1	2.36	1.06	4.6	0.79	23.5	0.36	25.0	6.4	5.1	9.0	0.69	0.33	2.29	21	**160**	**267**	0.94
85B	50.5	3.8	2.36	0.91	4.1	0.75	23.5	0.35	22.9	5.9	4.6	11.6	0.63	0.34	2.29	20	**155**	**222**	0.93
85F	40.8	3.6	2.22	1.10	4.0	0.74	18.4	0.31	19.6	5.0	4.0	7.3	0.60	0.30	1.99	22	**132**	**255**	1.11
86C	70.1	6.3	3.76	1.21	6.3	1.30	45.0	0.48	25.7	7.1	4.9	9.9	1.00	0.51	3.15	46	**233**	**523**	1.11
86D	12.5	3.8	3.08	0.54	2.6	0.93	6.9	0.53	6.7	1.6	1.7	13.9	0.51	0.46	3.16	30	**89**	**571**	2.54
86H	42.7	3.5	2.15	0.90	4.0	0.70	17.8	0.32	20.3	5.1	4.2	8.6	0.59	0.31	2.07	19	**132**	**262**	1.01
87B	51.00	10.10	5.48	2.36	10.40	1.97	14.30	0.75	40.80	8.94	10.90	18.40	1.73	0.79	5.09	44.30	**227**	**521**	1.76
87C	75.81	8.89	4.68	2.15	9.82	1.70	39.77	0.59	41.85	10.58	9.25	15.22	1.58	0.65	4.14	34.66	**261**	**1262**	1.13
87D	99.58	6.28	3.04	2.21	8.52	1.11	44.64	0.39	49.68	12.46	10.66	18.48	1.20	0.42	2.74	22.03	**283**	**446**	0.81
88A	74.90	11.20	6.01	2.46	11.90	2.14	24.70	0.79	46.10	10.80	11.40	16.20	1.93	0.85	5.44	47.20	**274**	**547**	1.37
88B	52.08	9.44	5.48	1.67	8.99	1.90	21.79	0.70	28.15	6.71	6.92	12.75	1.54	0.77	4.88	44.85	**209**	**577**	1.51
88B*	54.07	9.75	5.60	1.73	9.27	1.96	22.67	0.72	29.16	6.98	7.15	12.87	1.58	0.79	5.01	46.05	**215**	**589**	1.50
88C	70.02	10.08	5.53	2.03	10.51	1.98	32.81	0.69	36.49	8.90	8.67	12.29	1.70	0.76	4.79	44.22	**251**	**783**	1.28
89A	98.50	13.70	7.31	2.74	14.40	2.67	42.20	0.89	50.70	12.50	12.10	13.50	2.38	1.00	6.23	62.40	**343**	**835**	1.27
90A	134.00	14.50	7.12	3.41	16.40	2.70	52.30	0.84	67.00	16.70	15.70	15.90	2.63	0.96	5.98	55.90	**412**	**1017**	1.04
90C	88.65	7.34	3.69	2.06	9.00	1.33	35.54	0.47	45.35	11.40	10.04	15.78	1.36	0.52	3.35	27.13	**263**	**368**	0.92
91A	121.00	10.70	5.47	2.44	11.80	2.02	52.10	0.67	53.50	14.10	11.60	13.80	1.92	0.76	4.78	42.50	**349**	**984**	0.90
91B	35.85	2.73	1.32	0.87	3.44	0.49	15.86	0.17	17.03	4.35	3.68	6.59	0.51	0.18	1.21	8.83	**103**	**327**	0.83
92A	98.96	11.85	5.70	3.15	14.46	2.14	29.36	0.66	61.19	14.36	14.75	17.06	2.19	0.76	4.74	42.89	**324**	**841**	1.18
93A	115.89	18.19	8.91	4.42	21.18	3.32	45.09	1.04	81.05	19.00	20.10	22.06	3.26	1.19	7.41	66.85	**439**	**1555**	1.42

Appendix B. Rare Earth Concentrations and Outlook Coefficients (continued)

NDGS ID	Ce	Dy	Er	Eu	Gd	Ho	La	Lu	Nd	Pr	Sm	Sc	Tb	Tm	Yb	Y	ΣREE Whole	ΣREE Ash	C_{outl}
94A	63.89	7.84	4.15	1.71	8.41	1.50	32.88	0.51	34.03	8.70	7.49	9.03	1.36	0.58	3.61	30.99	**217**	**1410**	1.14
94B	30.87	5.74	3.63	0.80	4.65	1.23	17.97	0.49	13.21	3.33	3.14	8.80	0.87	0.52	3.38	33.39	**132**	**396**	1.58
95A	92.53	9.96	4.99	2.53	11.47	1.84	42.72	0.62	52.95	13.38	11.82	14.63	1.81	0.69	4.38	32.76	**299**	**811**	1.05
96A	62.35	7.55	4.25	1.39	7.55	1.50	32.76	0.51	26.48	6.88	5.67	13.08	1.25	0.58	3.62	39.03	**214**	**468**	1.17
96A*	64.84	7.84	4.41	1.44	7.87	1.56	33.94	0.53	27.42	7.18	5.84	13.56	1.30	0.60	3.71	40.41	**222**	**484**	1.16
97A	355.13	26.10	9.22	10.18	39.65	3.97	167.55	0.77	198.07	50.08	44.00	32.29	5.44	1.10	6.28	76.58	**1026**	**1718**	0.89
97A*	345.86	25.52	8.91	9.92	38.11	3.96	188.88	0.76	191.79	48.22	42.66	29.90	5.31	1.08	6.21	74.30	**1021**	**1710**	0.88
97B	178.11	14.09	6.73	4.46	18.57	2.55	92.63	0.69	97.65	24.62	19.59	16.06	2.63	0.88	5.19	54.40	**539**	**1939**	0.96